Synopsis
"Outline of tolerancing (from performance specification to toleranced drawings)"

By Robert H. Ginsberg
Hughes Aircraft Company
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Introduction

The author presents an optical design method and flow chart that emphasize consideration of component tolerances early in the design process. The paper elaborates on the proposed process by applying it to the design of two different optical systems. The author demonstrates the process of developing sensitivity tables and shows how to apply them to develop a tolerance budget.

First Order Optical Design

The general design process (figure 1) begins with the specification of performance requirements and consideration of mechanical constraints. These two parameters will define the complexity and physical limitations (size, shape, weight) that are imposed on the optical system. With these parameters defined, an engineer can begin a first order optical design. During this phase the optical engineer should periodically ensure that the optical design has not evolved to violate any of the mechanical constraints. Furthermore the designer should make sure that the optical design is being evaluated with the proper figure(s) of merit based on the performance requirements (table 1 gives examples of FOM). These figures of merit will be used later in the tolerance budget analysis.

Figure 1. Design and Tolerance Process Flow Chart[1]

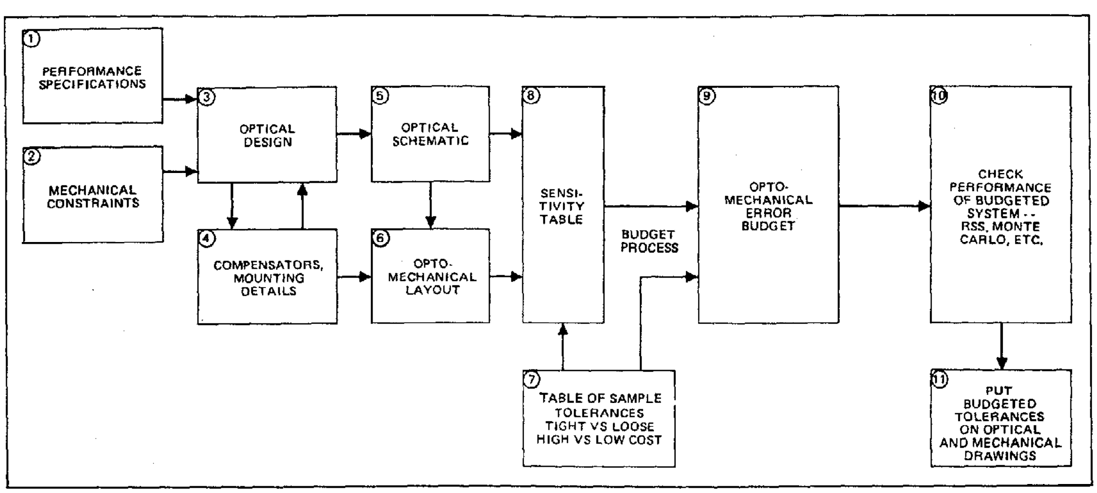


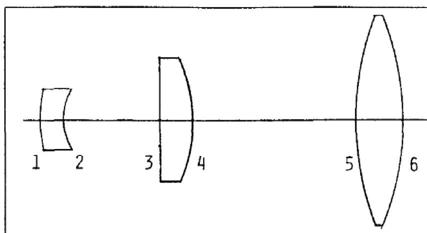
TABLE I. Performance Characteristics

1. Image quality, which can be expressed in terms of
   - MTF (geometrical or diffraction or other)
   - Resolution
   - Energy distribution in the image
   - Beam divergence
   - Geometrical aberrations, etc.
2. Boresight shift
3. Effective focal length
4. Magnifying power
5. Back focal length
6. Focus shift
7. Distortion
8. Tilt of final image plane
9. Displacement of final image from original axis,
10. etc.

Compensator Elements

As the optical design approaches an acceptable performance level, consideration of the compensator elements must be made. Each element that will act as a compensator must have its motion (axial, lateral, tilt) and the approximate throw of adjustment defined. The exact amount of compensation required of each element will not be known until a more thorough tolerance analysis has been completed. However, approximate amounts of compensation will help dictate the mechanical requirements and feasibility. If one finds that a lens must move an axial distance greater than the spacing between neighboring elements, a design change will be required. When the compensators have been adequately evaluated, the optical design schematic can be created (figure 2). Note that it is recommended to number the optical surfaces on the schematic to easily reference them during the tolerancing process.

Figure 2. Simple Optical Schematic Showing Numbered Surfaces[1]

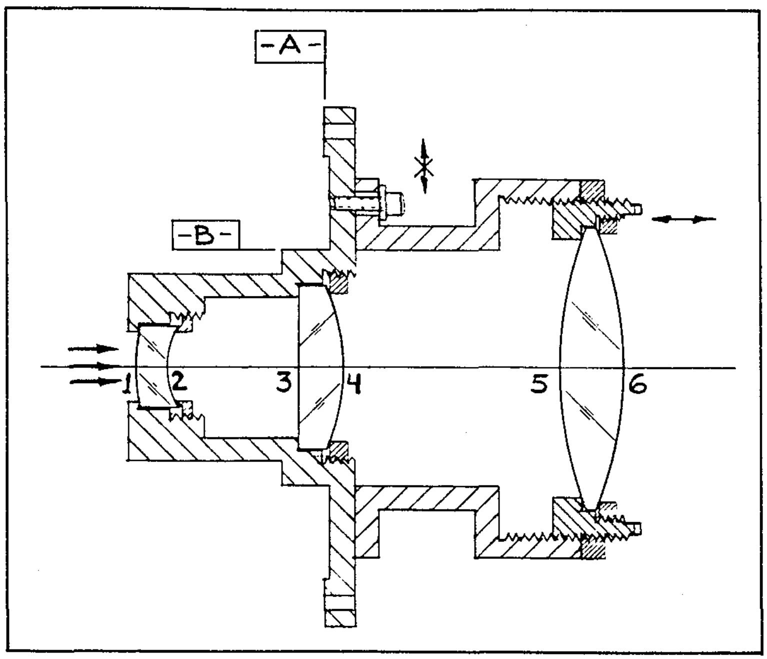


SURFACE	RADIUS	MATERIAL	THICKNESS	LIM. RAY
1				
2				
3				
4				
5				
6				

Opto-Mechanical Design

The optical design schematic and compensator requirements are used to create the opto-mechanical design. In creation of the opto-mechanical design, consideration will be made to the size and mounting limitations that may be present. Mechanical limitations of the compensator adjustments will become evident. Relative alignment of the optical components and key mounting surfaces will also become evident. Essentially, many of the features that require tolerancing will become evident from the mechanical design process. It is important that the optical and opto-mechanical engineers communicate during this process to ensure that the elements are mounted in a way that makes sense for the design. As an example, elements required for compensation must be mounted such that they can move in the desired direction with adequate resolution.

Figure 3. Example Opto-Mechanical Design Showing Critical Tolerances[1]

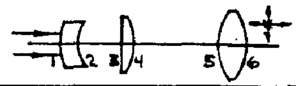


Sensitivity Table

By this time the mechanical design is completed and the sensitivity table can be created. A list of all of the possible errors must be created, including both optical elements and mechanical positions. This list requires considerations of how the mechanical system is defined and how optical components are constrained within it. The resolution of compensator movement must also be included on the list of sensitivities to be evaluated. An example of a list given by the author is shown in figure 4. Note that each surface is numbered in the same manner as the optical and opto-mechanical schematics. Each element will be perturbed from nominal by an amount that will result in a measurable effect on the figure of merit (FOM). If there is a compensator in the system that will compensate for the effect on the FOM, it must be optimized before evaluation of the FOM. The required amount of compensation for each sensitivity can be calculated or measured and filled into the table. Any compensator that is not used for a given sensitivity will be crossed out to prevent confusion.

Figure 4. Example Sensitivity Table Showing Surface Numbers and Compensators[1]

SENSITIVITY TABLE



5(a)

	SURFACE, ELEMENT OR GROUP	CHANGE	PARAMETER AND COMMENTS	ΔDIV. μRAD. (A)	REQ'D REFOCUS 5-6 INCHES	REQ'D DCNTR 5-6 INCHES
	1-2	.001	INDEX OF REFRACTION			X
	3-4	.001	" " "			X
	5-6	.001	" " "			X
	1-2	.00001	HOMOGENEITY		X	X
	3-4	.00001	"		X	X
	5-6	.00001	"		X	X
	1-2	.001"	THICKNESS OR AIR SPACE			X
	2-3	.001"	"			X
	3-4	.001"	"			X
	4-5	.001"	" (WITHOUT COMPENSATION)		X	X
	5-6	.001"	"			X
	1	.1%	RADIUS			X
	2	.1%	"			X
	4	.1%	"			X
	5	.1%	"			X
	6	.1%	"			X
	3	1 FRNG	NON-FLAT OVER . "ø			X
	1	1 FRNG	IRREGTY OVER . "ø		X	X
	2	1 FRNG	" " . "ø		X	X
	3	1 FRNG	" " . "ø		X	X
	4	1 FRNG	" " . "ø		X	X
	5	1 FRNG	" " . "ø		X	X
	6	1 FRNG	" " . "ø		X	X
	1-2	1 mr	WEDGE @2		X	
	3-4	1 mr	" @4		X	
	5-6	1 mr	" @6		X	
	1-2	.001"	ROLL @1		X	
	5-6	.001"	" @5		X	
	1-2	.001	DECENTER		X	

(A) AFTER REFOCUSING OUTPUT BEAM WITH LENS 5-6, OR CORRECTING OUTPUT BEAM DIRECTION WITH LENS 5-6.

The sensitivity table has given the relative component sensitivities to tolerances. It can be combined with a table of standard tolerances to develop an error budget. It is best to start with standard tolerances (figure 5) for all elements, and multiply them by the sensitivities from the sensitivity table. These errors can be summed in RSS to approximate the total system error. The contribution from each element to the total system error can be evaluated, and tolerances can be tightened beyond the standard tolerances. It is at this time that the designer must be careful to weigh cost and performance requirements with tolerances. In some cases, the optical system and/or mechanical system will require redesign in order to have reasonable/affordable manufacturing tolerances. This step is detailed in the more complete flow chart shown in figure 6. Ultimately, a tolerance budget can be created and tested with Monte Carlo simulations on most modern optical design software programs. This can yield insight to the percent yield of acceptable systems.

Figure 5. Example Machining and Optical Element Tolerance Tables[3]

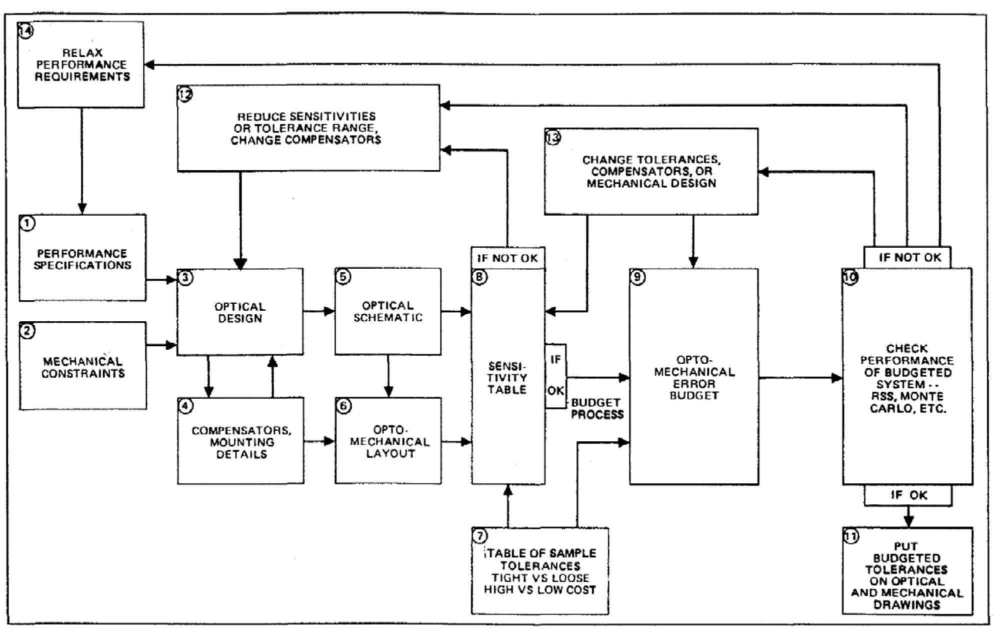
Tolerance Guide for Machined Parts

Machining Level	Metric	English
Coarse dimensions (not important)	±1 mm	± 0.040"
Typical machining (low difficulty)	±0.25 mm	±0.010"
Precision Machining (readily available)	±0.025 mm	±0.001"
High Precision (requires special tooling)	< ±0.002 mm	< ±0.0001"

Optical element tolerances

Parameter	Base	Precision	High precision
Lens diameter	100 µm	25 µm	6 µm
Lens thickness	200 µm	50 µm	10 µm
Radius of curvature			
Surface sag	20 µm	1.3 µm	0.5 µm
Value of R	0.5%	0.1%	0.01% or 2 µm
Wedge (light deviation)	5 arc min	1 arc min	15 arc sec
Surface irregularity	1 wave	λ/4	λ/20
Surface finish	50 Å rms	20 Å rms	5 Å rms
Scratch/dig	80/50	60/40	20/10
Dimension tolerances for complex elements	200 µm	50 µm	10 µm
Angular tolerances for complex elements	6 arc min	1 arc min	15 arc sec
Bevels (0.2 to 0.5 mm typical)	0.2 mm	0.1 mm	µ0.02 mm

Figure 6. Complete Design and Tolerancing Process Flow Chart[1]



Words of Wisdom

The author gives specific examples of how system limitations (mechanical and optical) can have effects on the tolerance budget. In many cases, the mechanical constraints will drive the optical design choices. The author also emphasizes the importance of clearly communicating information between the people working on the project. The optical and opto-mechanical engineer(s) must communicate requirements, sensitivities and complications effectively. Clear communication also applies to written documents. Tolerance budgets and sensitivity tables must be clearly labeled such that the data can be applied to the appropriate surface or element. Documents should be written so that they can be referred to in the future without ambiguity or confusion. The design process never begins and ends without iterative redesign, and this can only be accomplished if the communication is effective.

Comparison to Other Papers

While the focus of this paper is primarily on the process of tolerancing an optical system, there is an underlying concern of cost-benefit management. The purpose of evaluating and properly tolerancing an optical system to both ensure the system performs as expected and to assign the proper level of manufacturing tolerance (cost) for the components. In many cases cost is the limiting factor that will drive the design changes to achieve a desired performance specification. Another paper on tolerancing optical systems focuses on the approach of a cost-benefit analysis of each tolerance[2]. In this study, much as in the paper by Ginsberg, figures of merit for system performance are defined and evaluated for each tolerance feature. The relative sensitivities of each tolerance are weighed against a cost formula (equation 1) that estimates the cost of an element with a based on the level of tolerance assigned. In this manner, one may be able to achieve the same system performance with less expense by tightening the tolerances that will result in less of a cost increase.

Relative Cost of Tolerance on Parameter i $$\$_i = \frac{A_i}{T_i} + B_i \quad (1)$$

Figure 7. Relative Cost Analysis[2]

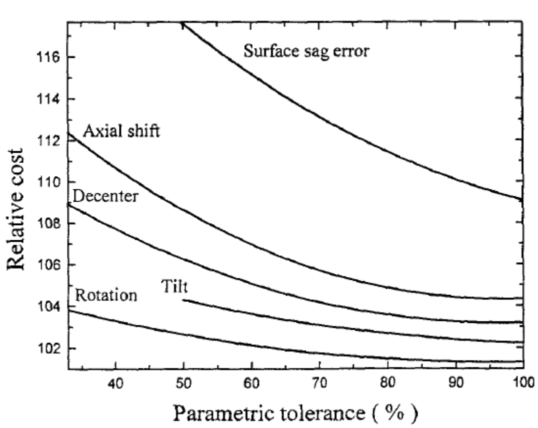


Fig. 13 Parameter tolerances versus relative cost for primary mirror of UV imager (base cost = 100)

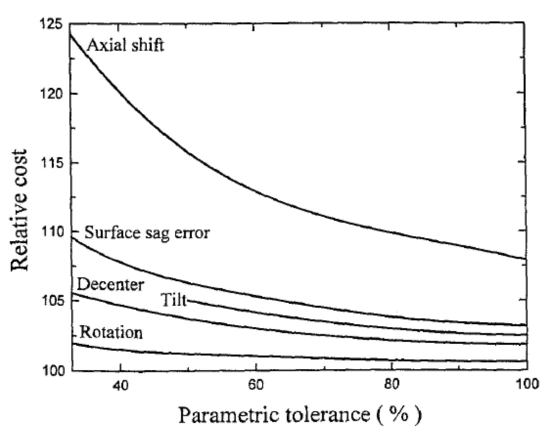


Fig. 14 Parameter tolerances versus relative cost for secondary mirror of UV imager (base cost = 100)

The relative cost analysis shown in figure 7 is an example of a very detailed relative cost analysis for a UV imager primary and secondary mirror tolerance budget. Based on equation 1, which details the cost of a tolerance on parameter i, based on its base cost and the cost of tightening the tolerance beyond the base tolerances of the fabrication shop[2]. This formula was evaluated (approximately) for each of the tolerances shown in figure 7, and their relative costs were shown as a percentage of the base tolerance. It is clear that surface sag error and axial shift are the two most expensive tolerances for the primary and secondary mirrors, respectively. The engineer could use this indication to see if the tolerance budget could be tightened on less expensive tolerances to achieve the same performance level. The paper by Ahmad[2] is a very detailed study on the cost-benefit relationship of tolerances. But it does compliment the process proposed by Ginsberg given that tolerancing any mechanical system is, in its very nature, a cost-benefit and performance analysis.

Conclusion

Both authors provide insight into the process of tolerancing an optical system. The primary point shared by both authors is the necessity of considering tolerances early and continuously in the design process. Iterations on the optical and opto-mechanical design will be required, and can only be successful if the proper considerations are made to the performance requirements, manufacturing limitations and cost.

References

1. Ginsberg, R., Outline of tolerancing (from performance specification to toleranced drawings), Optical Engineering 20(2) (March/April 1981) pp. 175-180.
2. Ahmad, A., Tolerance analysis versus image quality: a case study for cost-effective space optics, Optical Engineering 34(2) (February 1995) pp. 575-583.
3. Burge, J., Specifying Optical Components, Introduction to Opto-Mechanical Engineering Opti 521 Course Notes (Fall 2010).