Outline of tolerancing (from performance specification to toleranced drawings)

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Abstract. Tolerancing plans range in complexity from those in which all parameters are investigated, documented, and controlled, to those that rely solely on whatever quality of optics, mechanical parts, and assemblies is present. The level of complexity desired depends not only on technical considerations but also on cost, schedule, etc. An outline is presented which is applicable not only to the more complex tolerancing plans but also to more modest efforts. The various activities and documents of the complete tolerancing plan are described and illustrated with a view toward clarifying their functions. The outline together with the activities and documents should provide a point of departure for establishing an effective tolerancing plan in a given situation.

Keywords: optomechanical design; optical system tolerancing; optical drawings; specifications; error budgets.

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1. INTRODUCTION

Everyone who produces an optical system utilizes some method of tolerancing. At one extreme, a system consisting of optics ordered "off the shelf" from a surplus company or that is assembled from the contents of a drawer marked "Lenses and Prisms" employs the most basic method of tolerancing; that is, using the quality of the available components. On the other hand, the method of tolerancing presented in this paper may appear to be the other extreme; that is, it may seem to be so complicated that it would never be used. It is hoped that this is not the case. In its complete form, the outline merely indicates the documents and operations that are useful, and the refining options that are available for tolerancing an optical system. All of these documents, operations, and options are in current use in the optomechanical community, although often under different labels and sometimes not formally recognized as such. It is hoped that formalizing the outline will bring about a better understanding of the tolerancing process and thereby make it more useful and easier to implement.

2. BASIC OUTLINE

The basic outline, which is an extension of that presented by Olson,[1] is shown in Fig. 1. It begins with Item 1, a document labeled "Performance Specifications," which could also be called system requirements, and ends with Item 11, putting tolerances on the optical and mechanical drawings. The purpose of the process shown in this figure is to determine the loosest tolerances that can be specified for optical and mechanical parts and assemblies which will still provide adequate performance. It is assumed that using tolerances that are tighter than necessary (and therefore more expensive in terms of both money and time) is as undesirable as using tolerances that are so loose that the performance of the resulting system is unacceptable. When this assumption is not warranted, a partial use of the process can still give visibility of the relationship between the tolerances used and quality of performance. Table 1 lists the parameters for which performance specifications are often written.

Item 2 in Fig. 1 shows that the system is constrained by certain mechanical considerations, such as size, weight, and configuration, all of which could be included in the specifications for Item 1 but which for clarity are treated separately. Figure 2 is an example of mechanical constraints on the design of a military telescope; it shows the required location for the objective and exit pupil together with the space envelope that must not be exceeded.

On the basis of Items 1 and 2 in Fig. 1, the optical design can be started, as shown in Item 3. The optical design will not be considered finished until the satisfactory completion of the performance check of the budgeted system, Item 10.

Before the optical design has progressed beyond the first-order layout, the layout should be checked against the mechanical constraints to ensure that it does not conflict with them. In the example (Fig. 2), it should be determined that (1) the image in the eyepiece is properly oriented and (2) the positions of the relay lenses are away from the locations of the prisms and mirrors. These requirements can be easily overlooked if the optical layout is considered only in the straight-through format of the usual computer pictorial printout.

When the optical design has begun to firm up, it is time to consider any elements that are to be used as compensators for the system tolerances and to consider certain mounting details (Item 4 in Fig. 1). One compensator might be an element or group of elements whose motion refocuses the image at the required location; it is usually a focusing lens, but it could be a variable airpath prism assembly. Another compensator might be an element or group of elements whose motion recenters the axial image to correct the line of sight. A third compensator might be an element or group of elements whose motion compensates for the aberration introduced by the system tolerances. An example of a mounting detail that should be considered during the early portion of the optical design is the choice of a cemented doublet, a doublet air-spaced with a spacer, or an air-spaced doublet having edge contact.

Further insight into the importance of establishing the compensators and certain mounting details early in the optical design can be gained by again referring to Fig. 2. For example, placing the reticle on the field lens bonded to the folding prism will require that the objective lens be used as the focus compensator to bring the primary image to the reticle plane, compensating for tolerances as well as focusing on near objects. Also, if the relay lens is to be used as a second focus compensator to bring the secondary image to the eyepiece focal plane, sufficient clearance must be provided between the relay lens and the folding mirrors for the required focus motion.

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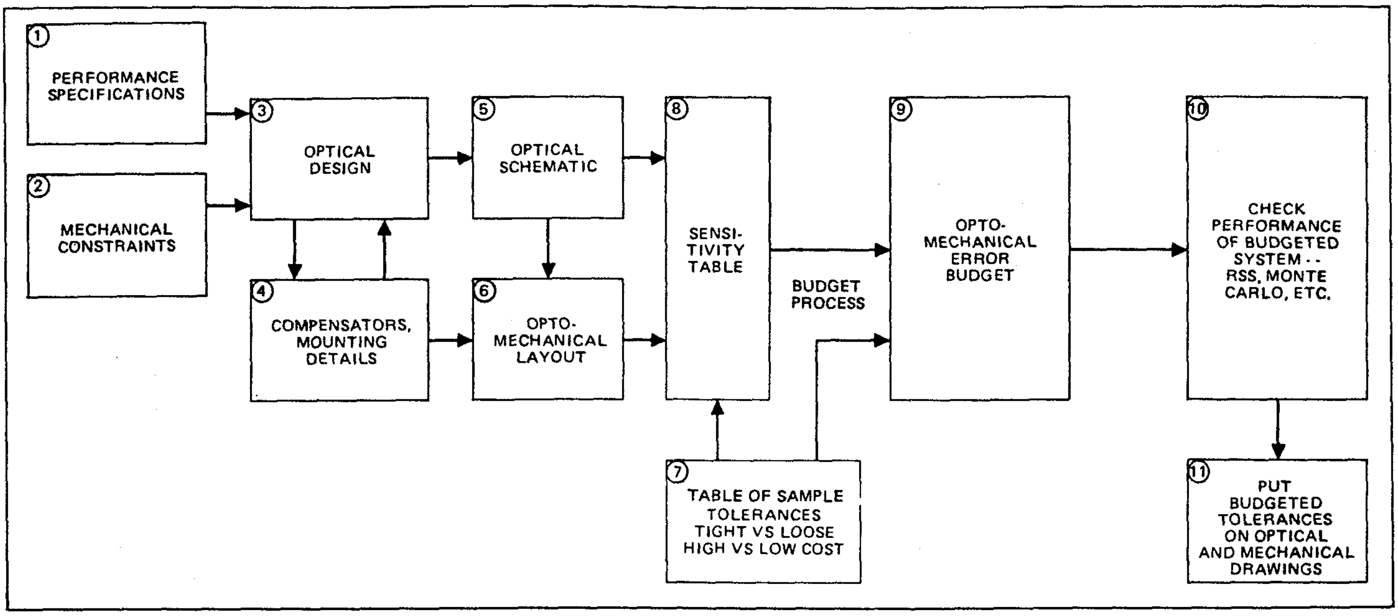


Fig. 1. Basic outline of tolerancing.

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.

The amount of focus motion needed will have to be estimated because the exact amount will not be known until the error budget (Item 9 in Fig. 1) has been completed. Also if the magnification of the relay is close to 1:1, it may even be impossible to use the entire relay lens as a focus compensator because of the minimum object-to-image distance effect; in that event, the relay lens might be split into two doublets, one of which would be focusable. The point to be made is that these problems should be discovered as early as possible in the optical design.

3. OPTICAL SCHEMATIC

After the initial optical design has been performed, the optical schematic or what some call "the prescription" can be drawn. (Item 5 in Fig. 1). Figure 3 is a form for the optical schematic of a laser beam expander telescope. For convenience, this telescope will be used as the example to illustrate some of the remaining items in the outline.

An important feature of the optical schematic is that each optical surface is numbered, and each number will be used to denote the corresponding surface in the sensitivity table and error budget to be described later. Although it is not always possible for the computer to use the same numbers as those on the optical schematic, to prevent confusion it is imperative that the surface numbers given on the computer printout be changed to those on the optical schematic for use in the sensitivity table and error budget.

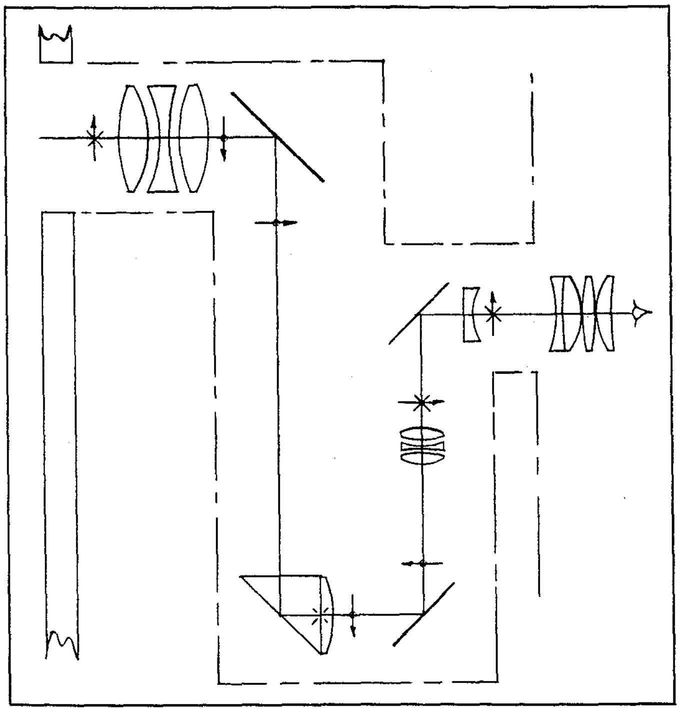
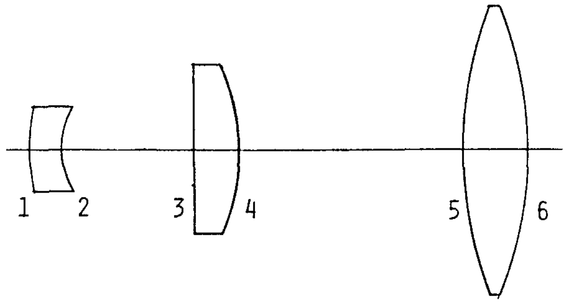


Fig. 2. Example of mechanical constraints.

That leads to one of the most important considerations in this paper, the problem of communication between and among the various people involved in the process. They might include the systems engineer, the optical designer, the optomechanical engineer, the mechanical designer, the electrical or electronics engineer, and the draftsperson. Sometimes all of these functions are performed by one person, whose problem is then not one of communication but of visibility of the data. Generally, however, a number of people are involved in the process and the success of the program therefore requires the accurate transmission of information. The format and content of each of the documents described herein should be designed to most clearly convey the information they contain. A stack of computer printouts requiring a refresher course in interpretation every time it is used does not qualify. If a person has been shown the document, and if the meaning of the various features has



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

Fig. 3. Optical schematic.

been discussed, the document should then be self-explanatory. Even a year later, it should still be self-explanatory.

4. OPTOMECHANICAL LAYOUT

When the optical schematic has been completed, the optomechanical layout can be drawn (Item 6 in Fig. 1). Figure 4 is an optomechanical layout of the laser beam expander telescope that was previously shown. This layout should illustrate the possible optomechanical and mechanical errors to be used in calculating the sensitivity table, just as the optical schematic does for the optical parameters. It should show which elements are used as compensators and how they are moved. It can be seen in Fig. 4 that the telescope will be mounted at plane "A" and located with respect to diameter "B." The laser beam will be incident perpendicular to plane "A" and centered on the hole that locates diameter "B." Lens 5-6 will be used as a compensator for focusing the output beam and also for aligning the output beam to be perpendicular to plane "A." Because lens 1-2 will seat on surface 1, any looseness between its outer diameter and the metal inner diameter can allow the lens to roll about the center of curvature of surface 1; however, an error in the position of the metal inner diameter with respect to the inner diameter for lens 3-4 can result in a pure decenter or, in other words, a translation perpendicular to the optical axis. (Lens 3-4, on the other hand, is mounted on its plano surface and so therefore it cannot roll but can only decenter). Lens 1-2 will tilt if the shoulder against which it is mounted is tilted with respect to surface "A." Because lens 1-2 is seated on surface 1, if it is assumed that the lens diameter is perfectly centered in its cell, the "optical decenter" or "deviation" of the lens is then best expressed as a "wedge"; that is, a tilt of surface 2 about its vertex. (For completeness, it should be stated that (1) the optical decenter, (2) deviation, (3) wedge, (4) TIR of the image or lens diameter, and (5) edge thickness difference are merely different ways of describing the same phenomenon.)

For a more complex system, the optomechanical layout will also show which *groups* of elements are to be decentered, axially translated, or tilted. For a simple system, such as the three-element beam expander telescope, it is easy to calculate the effect of rolls, decenters, and tilts for all elements and groups, using each element as a compensator in turn without worrying about which calculations are unnecessary. For a more complex system it is not practical to calculate sensitivities for all possible error geometries and compensators.

One more document is needed before the sensitivity table can be started; that is the sample tolerance table (Item 7 in Fig. 1). An example is shown as Table II. It gives values for relatively tight and relatively loose tolerances (or relatively high or low cost) for each of the parameters to be considered in the sensitivity table.

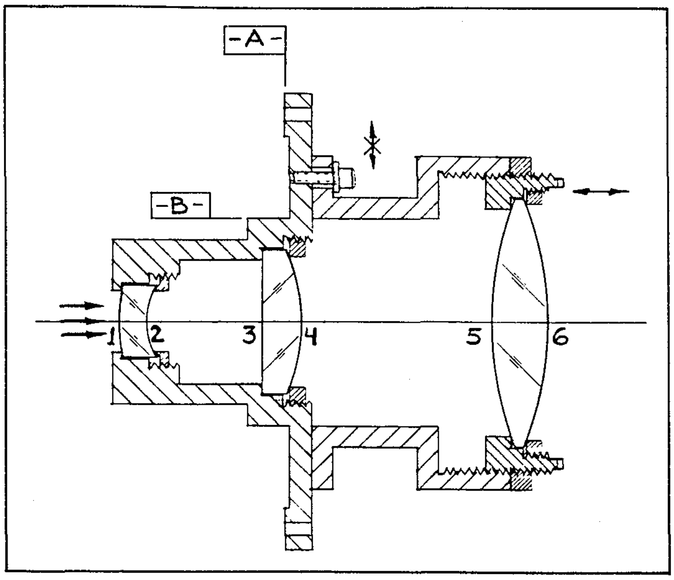


Fig. 4. Optomechanical layout.

TABLE II. Sample Tolerances

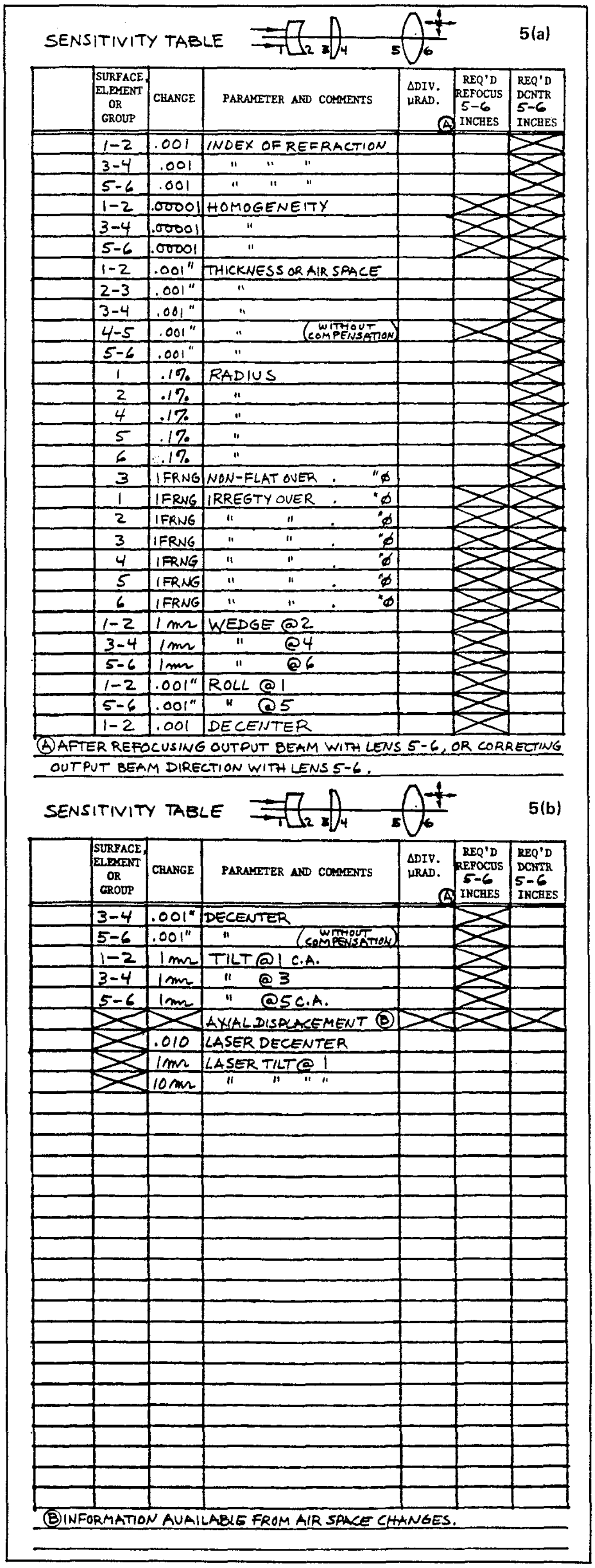
Parameter	Tolerance Fairly Tight	 Fairly Loose	Units
Index of refraction	0.0003	0.003	———
Change in radius	5	30	fringes*
Departure from spherical or flat	1/8	4	fringes*
Irregularity, astigmatic	1/8	2	fringes*
Irregularity, random	1/8 to 1**	1 to 10**	fringes per inch*
Thickness	0.002	0.004	inches
Airspace	0.002	0.010	inches
Decenter, optical	1/2	5	minutes of arc
Decenter, mechanical	0.001	0.010	inches
Translation along optical axis	0.001	0.010	inches
Tilt	0.3	2	milliradians
Lens roll	0.001	0.010	inches
Dimension errors of prisms	0.001	0.010	inches
Angular errors of prisms and windows	1/2	5	minutes of arc

*One fringe is equal to one-half wavelength at $\lambda = 0.5461$ μm (mercury green). Fringes are specified over the maximum diameter (or dimension) of the clear aperture.

**Depends on the manufacturing process.

5. SENSITIVITY TABLE

Now the sensitivity table (Item 8 in Fig. 1) can be started. Figure 5 is an example of a sensitivity table form for the laser beam expander telescope previously shown. At the top is a simple sketch of the optics, with the same numbering that was used on the optical schematic. For more complex systems, of course, the optical schematic can be attached to the table. The first column is for the surface or element (or group of elements) to be changed; a group of elements is denoted by the first and last surfaces separated by a dash. The second column is for the amount of change to be introduced. The third column is for the parameter whose value is to be changed. The fourth column is for the change in the performance characteristic of interest,



SENSITIVITY TABLE 5(a)

	SURFACE, ELEMENT OR GROUP	CHANGE	PARAMETER AND COMMENTS	ΔDIV. μRAD. Ⓐ	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	1FRNG	NON-FLAT OVER . "ø			X
	1	1FRNG	IRREGTY OVER . "ø		X	X
	2	1FRNG	" " . "ø		X	X
	3	1FRNG	" " . "ø		X	X
	4	1FRNG	" " . "ø		X	X
	5	1FRNG	" " . "ø		X	X
	6	1FRNG	" " . "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	

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

SENSITIVITY TABLE 5(b)

	SURFACE, ELEMENT OR GROUP	CHANGE	PARAMETER AND COMMENTS	ΔDIV. μRAD. Ⓐ	REQ'D REFOCUS 5-6 INCHES	REQ'D DCNTR 5-6 INCHES
	3-4	.001"	DECENTER		X	
	5-6	.001"	" (WITHOUT COMPENSATION)		X	
	1-2	1 mr	TILT @1 C.A.		X	
	3-4	1 mr	" @3		X	
	5-6	1 mr	" @5 C.A.		X	
	X	X	AXIAL DISPLACEMENT Ⓑ	X	X	X
	X	.010	LASER DECENTER			
	X	1 mr	LASER TILT @ 1			
	X	10 mr	" " " "			

Ⓑ INFORMATION AVAILABLE FROM AIR SPACE CHANGES.

Fig. 5. Sensitivity table.

in this case, the increase in the output beam divergence. The circle in the heading of Column 4 refers to a note that clearly specifies that a particular element compensates for defocus or change in direction of the output beam before the increase in beam divergence is calculated. Column 5 is for the amount of axial translation of the compensator required to refocus the beam, and its heading states which element is being moved. Column 6 is for the amount of decenter of the compensator required to recenter the output beam and its heading states which element is being moved. Further columns could be added to show how the listed change in parameter affects other performance criteria. In fact, any of the performance criteria listed in Table I could be treated in this way.

One often wants to know the performance change if the compensator is moved slightly from its nominal position. To get that information, one can ask for a change without compensation, as was done for airspace 4-5 and decenter of element 5-6. Axial displacement was not listed because the airspace changes provided the same information in this three-element system.

A very obvious feature of the sensitivity table is the large X that is used to show which spaces need not be filled in. This expedient not only saves time but also emphasizes even more clearly that every space which has not been crossed out must be filled in.

It should be emphasized that the only way one can be sure to get all of the information desired for the sensitivity table is to prepare a skeleton table as shown here with all the specific line entries and blank spaces to be filled in. In spite of every good intention, a person running the sensitivity program on a computer cannot remember what is wanted unless it is clearly recorded.

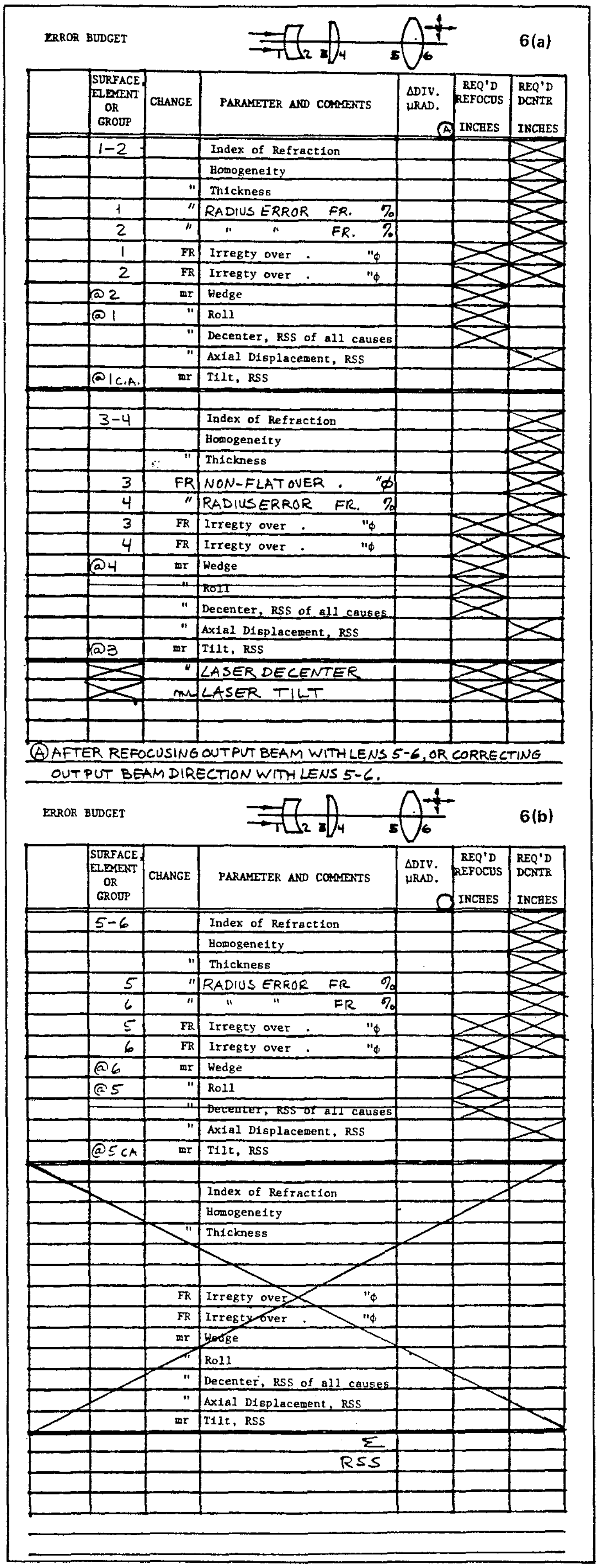
In entering the changes in Column 2, it is desirable to use 0.001 for index, 0.00001 for homogeneity, 0.001" for thickness, etc., because of the ease with which the error budget can be filled in later. This remark applies to those performance criteria whose changes are linear with the changes in Column 2 for small changes. It does *not* apply to MTF, for which a slightly more complicated relationship holds.

For "Roll," the surface about which the element is to be rolled is noted; for "Tilt," the position of the pivot axis is noted. In the example shown, the effect of tilt and decenter of the laser is also listed.

6. ERROR BUDGET

When the blank spaces in the sensitivity table have been filled in after the appropriate sensitivity runs on the computer, then the sensitivity table is used together with the table of sample tolerances to prepare the optomechanical error budget (Item 9 in Fig. 1). Figure 6 is the error budget form for the laser beam expander telescope. The format is almost identical to that of the sensitivity table; however, one obvious difference is that all of the parameters for a given element are treated in order as opposed to the listing of a particular parameter for all of the elements. This arrangement will be convenient when transferring the tolerances from the error budget to the optical and mechanical drawings, because all of the tolerances for a given element are grouped together. Another reason for using this format is that it allows one to duplicate the blank forms in advance, complete with appropriate X marks, saving a great deal of time for a system with many elements. The space on the form for entering "RADIUS ERROR" or "NON-FLAT" is left blank in order to accommodate spherical or plano surfaces. When an element is not subject to a particular error, such as "Roll," the appropriate line is crossed out.

Aside from format, the major difference between the error budget and the sensitivity table is that in the error budget, the magnitude of each change is chosen so that the performance will be degraded by an amount not to exceed a preset limit. The limit can be determined in a number of ways. Assume, for example, that the allowable increase in the beam divergence of the beam expander telescope due to all fabrication and assembly tolerances is 100 μrad, and that 50 changes (tolerances) are listed in the budget. One simple way to determine the limit for any single performance change is to rss or root sum square. In the example given, $\sqrt{50x^2} = 100$ μrad; therefore $x = 14$ μrad and the changes in each parameter will be chosen so that no line has a ΔDIVERGENCE of more than 14 μrad. Also, if the total motion of a



ERROR BUDGET

6(a)

	SURFACE, ELEMENT OR GROUP	CHANGE	PARAMETER AND COMMENTS	ΔDIV. µRAD. Ⓐ	REQ'D REFOCUS INCHES	REQ'D DCNTR INCHES
	1-2		Index of Refraction			X
			Homogeneity			X
		"	Thickness			X
	1	"	RADIUS ERROR FR. %			X
	2	"	" " FR. %			X
	1	FR	Irregty over . "ϕ		X	X
	2	FR	Irregty over . "ϕ		X	X
	@2	mr	Wedge		X	
	@1	"	Roll		X	
		"	Decenter, RSS of all causes		X	
		"	Axial Displacement, RSS			X
	@1 C.A.	mr	Tilt, RSS			
	3-4		Index of Refraction			X
			Homogeneity			X
		"	Thickness			X
	3	FR	NON-FLAT OVER . "ϕ			X
	4	"	RADIUS ERROR FR. %			X
	3	FR	Irregty over . "ϕ		X	X
	4	FR	Irregty over . "ϕ		X	X
	@4	mr	Wedge		X	
		"	~~Roll~~		X	
		"	Decenter, RSS of all causes		X	
		"	Axial Displacement, RSS			X
	@3	mr	Tilt, RSS			
	X	"	LASER DECENTER		X	X
	X	mr	LASER TILT		X	X

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

ERROR BUDGET

6(b)

	SURFACE, ELEMENT OR GROUP	CHANGE	PARAMETER AND COMMENTS	ΔDIV. µRAD. ○	REQ'D REFOCUS INCHES	REQ'D DCNTR INCHES
	5-6		Index of Refraction			X
			Homogeneity			X
		"	Thickness			X
	5	"	RADIUS ERROR FR %			X
	6	"	" " FR %			X
	5	FR	Irregty over . "ϕ		X	X
	6	FR	Irregty over . "ϕ		X	X
	@6	mr	Wedge		X	
	@5	"	Roll		X	
		"	~~Decenter, RSS of all causes~~		X	
		"	Axial Displacement, RSS			X
	@5 CA	mr	Tilt, RSS			
			~~Index of Refraction~~			
			~~Homogeneity~~			
		~~"~~	~~Thickness~~			
		~~FR~~	~~Irregty over "ϕ~~			
		~~FR~~	~~Irregty over . "ϕ~~			
		~~mr~~	~~Wedge~~			
		~~"~~	~~Roll~~			
		~~"~~	~~Decenter, RSS of all causes~~			
		~~"~~	~~Axial Displacement, RSS~~			
		~~mr~~	~~Tilt, RSS~~			
			Σ			
			RSS			

Fig. 6. Error budget.

compensator is limited, a similar calculation can set a limit to the compensator motion allowed for each line entry. (It should be noted that for more complex systems than that described here, a half dozen "performance" columns could be used, each having a system specification and therefore each requiring a preset limit for the line entries.) Note that the preset limits may be changed after the initial budget has been analyzed.

The theoretical goal of the error budget is to change each parameter by such an amount that each change will degrade the performance by an identical amount and within the preset limit. In that way none of the parameter changes will dominate the performance degradation. In practice, certain parameters will be much more sensitive than others, and changes in them must be kept very small in order to stay within the present limit. For some parameters the limit must be exceeded because it is not desirable to use the required tight tolerance; such exceptions should be kept to a minimum. Other parameters will be so insensitive that even using a very liberal change will alter the performance only an insignificant amount in comparison with the preset limit. The budget process is an attempt to find changes in each parameter that are reasonable in cost, and that degrade the system by an amount within the preset limit.

It will be noted on the error budget shown that for each element a line is provided for Decenter, Axial Displacement, and Tilt. Each of these changes can be the result of several different changes. For example, the tilt of an element may be the result of two or more mechanical tilt tolerances. For the budget format shown, it is convenient to list only the resultant parameter change, in this case one that is based upon an rss of the individual changes. On a subsequent page of the budget, each of the individual changes can be listed separately so that all of them can be considered in a Monte Carlo analysis on a truly random basis and so that the changes for each line item can also be used to tolerance the mechanical drawings.

A number of computer programs are available that can generate sensitivity tables automatically or semi-automatically. Some of these combine the sensitivity table and the error budget in what is called an inverse sensitivity table; the performance change in the right-hand column is kept constant while the parameter changes in the left-hand column are allowed to vary. Some common sense must still be used before applying the results of an inverse sensitivity table. For example an inverse sensitivity table might indicate that a filter plate can be tilted by 10°; for obvious mechanical reasons that tolerance would be reduced to 1° or less.

Some tolerancing programs cannot include in their budgets more than one input of a specific parameter change for a specific element. Assume, for example, that a lens element is subject to decenters because of the error in position of (1) the lens with respect to the cell inner diameter, (2) the cell inner diameter with respect to the cell outer diameter, and (3) the cell outer diameter with respect to the main lens cell. If the computer program cannot handle three different decenters for a given element, one must divide the allowable parameter change among the three, perhaps by rss. Conversely, one should be sure that there is enough allowable change so that it can be subdivided reasonably into three separate tolerances.

When the error budget has been "smoothed out," the resultant performance of the budgeted system should be determined (Item 10 in Fig. 1). For some characteristics, such as increase in beam divergence or the required motion of the compensators, a simple rss treatment of the right hand columns may suffice. If the performance characteristic is "change in MTF," however, a Monte Carlo or similar procedure may be required.

When the rss or Monte Carlo analysis has shown that the budgeted parameter changes will produce an optical system with the required performance, those changes can be used as tolerances for the optical and mechanical drawings, (Item 11 in Fig. 1).

7. COMPLETE OUTLINE

Everything that has been described so far has assumed that there are no serious roadblocks in the process for performance specificatin to tolerances on the drawings. Unfortunately that is not always the case.

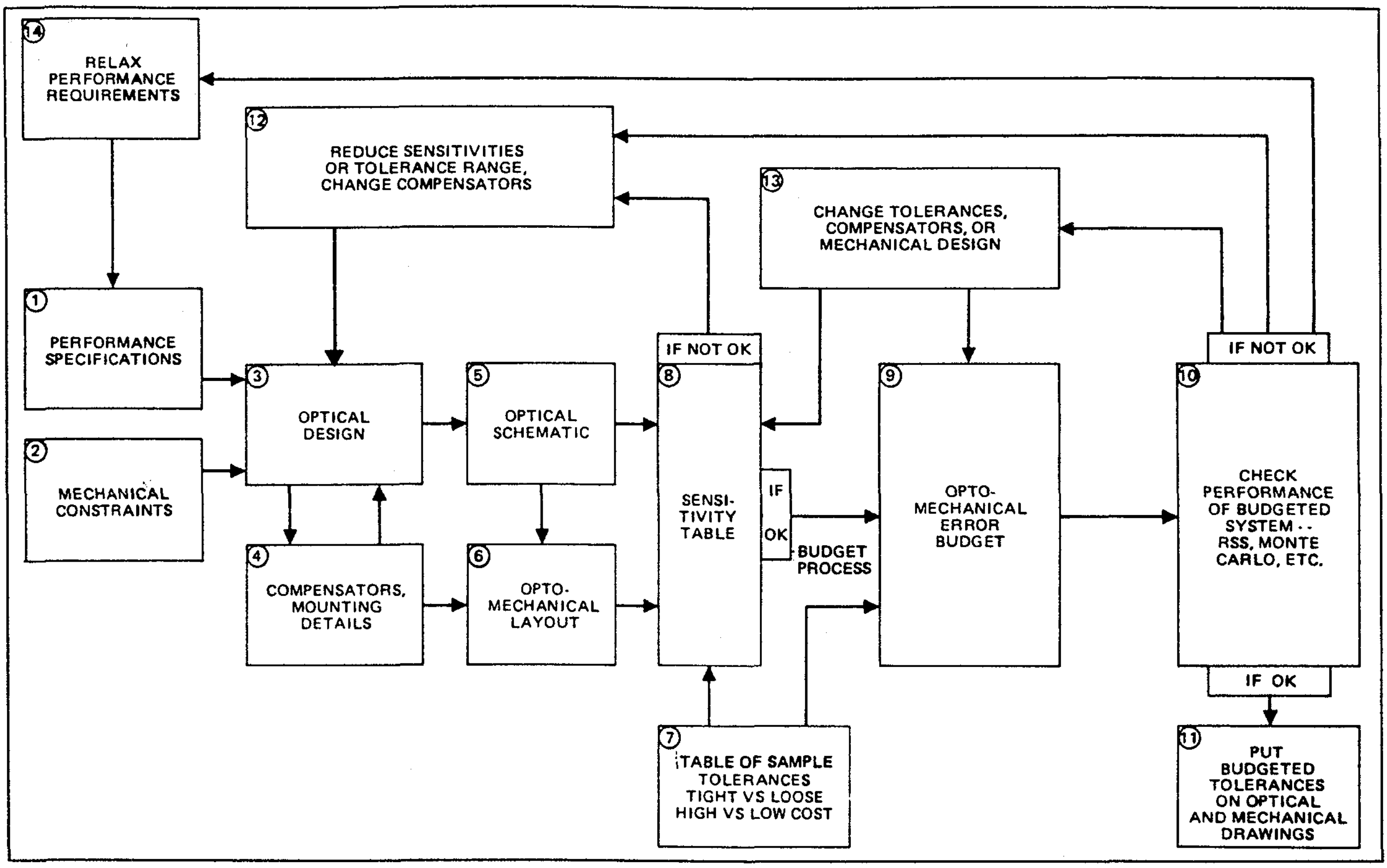


Fig. 7. Completed outline of tolerancing.

Figure 7 is a more complete version of the tolerancing outline, giving various options for surmounting the roadblocks in the process.

Referring to Item (8) in Fig. 7, the sensitivity table may be "Not OK"; even before one starts the error budget, it may be obvious that to meet the required performance the tolerances would be too tight, and therefore too expensive. In fact, the tolerances might be impossible to achieve at any cost. If the sensitivity table is "Not OK," one can go back to the optical design via Item 12 in Fig. 7, to "reduce sensitivities or tolerance range or change compensators." If, for example, an index of refraction is too sensitive, one can use the values of index of refraction and dispersion from the melt data of a specific lot of glass and reoptimize the design. If a radius of curvature is too sensitive, one can choose the radius of an available test glass and then reoptimize the design, the only tolerance on radius being the accuracy with which the test glass was measured; test glasses can be measured more accurately than they can be produced.

Sometimes the problem in sensitivity is the choice of compensators. One can try different compensators to see if any improvement is possible.

If the air space of an air-spaced doublet is too sensitive for wedge, one can redesign for edge contact to eliminate the spacer or, if possible, one can use a cemented doublet.

Assume that the sensitivity table can be made acceptable, that an error budget is prepared, and that the performance predicted by an rss or a Monte Carlo analysis is unacceptable. One can go back to the error budget via Item 13 in Fig. 7 to "change tolerances, compensators, or mechanical design." If the error budget includes a few very sensitive items, one can consider tightening these even further. If the error budget has already been reasonably "smoothed out," one can consider tightening all the tolerances by a given percent. One can consider changing the relative orientation of the elements in assembly as a compensator, an operation which is absolutely necessary, for example, in producing microscope objectives with high numerical apertures. One can also change the mechanical design to provide additional motions for compensation. The question might be asked, "Why wait until now to introduce some of these changes?" The answer is that the first attempt should be to design a system that is most easily produced; the design should then be changed only as required.

After making the changes in Item 13 in Fig. 7, one can go back to the error budget or perhaps back to calculate new values for the sensitivity table. If after all this is done the performance in Item 10 in Fig 7. is still unacceptable, one can go back to change the optical design via Item 12. Of course, if all else fails, one can always try to get the performance requirements changed, a tactic that was perhaps used before without success, but one that can now be attempted again with the backup of all of the documentation that has been generated.

In conclusion, it is to be hoped that the overall process described in this paper will give a better insight into the optical system in question and that it will produce an error budget whose parameter changes can be used effectively to tolerance the optical and mechanical drawings.

8. REFERENCE

1. Olson, V., Musing, Ramblings, and Ruminations on Optical Specifications, Optics News, (Fall 1977). pp. 14-16.