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FUNDAMENTALS OF ESTABLISHING AN OPTICAL TOLERANCE BUDGET

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ABSTRACT:

The basis for, and the specific steps involved in, the determination of a suitable tolerance budget are discussed, using an R.S.S. (square Root of the Sum of the Squares) statistical addition of the tolerance effects. A numerical example is given.

I INTRODUCTION

When an optical system is designed, the performance of the nominal "paper" design is normally somewhat better than the performance specifications require, in order to allow for the degradation expected to result from the fabrication tolerances. The determination of the fabrication tolerance budget should balance the relative sensitivity of the individual construction parameters against the cost of maintaining the tolerances in such a way as to assure the performance of the optical system in the most economical fashion.

We will consider first the manner in which the effects of tolerances can be expected to combine, and the statistics of the combination of several tolerance effects. Then we will take up the establishment of a performance requirement based on wavefront deformation (Optical Path Difference, or OPD).

The resultant of a trial tolerance budget is determined by calculating a "change table", that is, a table of the partial differentials of the aberrations (and any other significant system characteristics) with respect to the construction parameters of the lens. The individual effects of the tolerances are combined by taking the square root of the sum of the squares of the effects. This is compared with the performance requirement, and the trial budget is then adjusted to achieve conformance with the goal.

II THE STATISTICS OF AN ASSEMBLY OF SEVERAL COMPONENTS

We approach this aspect of the subject through a hypothetical, but not unrealistic, example. Assume that the SPIE Manufacturing Company makes a line of products which are simply stacks of disks, each disk 0.1 inch thick. Our model Mark-1 consists of one disk, Mark-2 is two disks, Mark-3 is three disks, etc. The SPIE production machinery can control the disk thickness to ± 0.005 inch. Our problem is to determine what tolerance on total thickness we can hold for Mark-1, Mark-2, etc.

Let us make a simple, slightly unrealistic, but conservative, assumption about the SPIE production process, namely that each disk is equally likely to be made to any thickness within the toleranced range of 0.1 inch ± .005 inch. This is called a uniform, or rectangular, probability distribution, and is plotted in Fig. 1. What this means is that the probability of a disk being fabricated in the thickness range between, say, .095 inch and .096 inch is one in ten; this is the portion of the area under the curve between those two thicknesses (shown shaded) as a fraction of the total area under the curve.

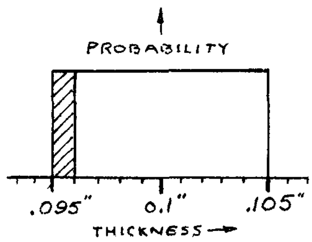

Fig. 1 - Uniform probability distribution

Thus for our Mark-1 model, consisting of only one disk, the situation is quite clear. We can guarantee that 100% of the product will fall between a thickness .095 inch and a thickness of 0.105 inch. If we wanted to accept a 20% rejection rate at final inspection, we could establish a product tolerance of .096 inch to .104 inch, and so on.

Our Mark-2 product, consisting of a stack of two disks, obviously has a nominal thickness of 0.2 inch, and the total range of thickness permitted by our ± .005 inch individual disk tolerance is equally obviously .190 inch to .210 inch. However, the probability distribution is no longer uniform. As we have seen, the probability of the first disk being made between .095 and .096 inch is one in ten; the probability is exactly the same for the second disk. Therefore, the probability that both disks in the same assembly will fall into this range is one-tenth of one-tenth, or one in one-hundred.

This means that only 1% of our Mark-2 assemblies can be expected to fall in the total thickness range of .190 to .192 inch. Similarly, the probability is one in four hundred (0.25%) that the assembly will have a thickness between .190 and .191 inch. The probability distribution curve for the Mark-2, two-disk assembly, is shown in Fig. 2; it is far from uniform; its shape is triangular. It can be seen that three-quarters of the assemblies will fall between .195 inch and .205 inch, which is just one-half the possible total range of .190 inch to .210 inch. Thus, the effect of a multiple component assembly is to concentrate its characteristics about the nominal values and to reduce the number of assemblies that take on values at the extreme ends of the possible tolerance range.

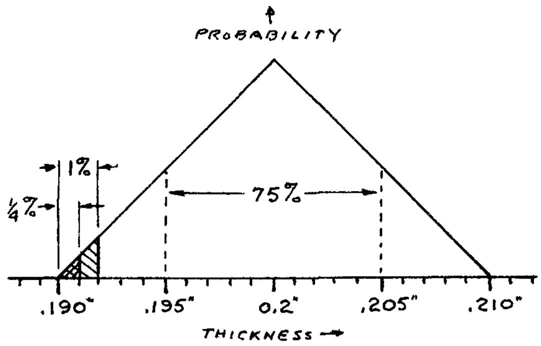

Fig. 2 - The probability distribution for an assembly of two disks, each of which has a uniform probability distribution.

Figure 3 shows the situation for assemblies consisting of 1, 2, 4, 8 and 16 pieces. Each probability distribution curve has been normalized so that the total range of the tolerance is the same, and also so that the area under each curve is the same. It is quite obvious that the more parts (or tolerance effects) there are to an assembly, the more concentrated the distribution becomes about the nominal value, and the smaller the percentage of assemblies which are at the extremes of the total tolerance range. Figure 4 illustrates this situation in another way, showing the fraction of the total possible tolerance range which will contain a given percentage of all the assemblies as a function of the number of parts in the assembly.

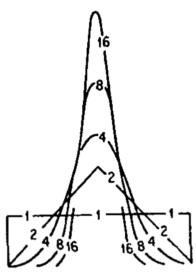

Fig. 3 - The more components there are in an assembly, the greater the probability that the characteristics will be near their nominal value.

The importance of this is quite straightforward. If we can accept a relatively modest rejection rate in final assembly, we can increase the individual piece-part tolerances by a significant factor over the level which would otherwise be required to guarantee that 100% of the assemblies would be within the same range. For example, in our Mark-16 product, containing 16 disks with a nominal thickness sum of 1.6 inch and a possible total tolerance range of ± .08 inch, Fig. 4 indicates that less than 0.2% of the assemblies will exceed a tolerance of ± .04 inch, which is only half of the total possible range.

Thus, we could either 1) specify our Mark-16 product at 1.6 inch ± .04 inch or 2) use a less expensive production technique which produced a piece-part tolerance of ± 0.010 inch and specify the product at 1.6 inch ± .08 inch. In either case, we could require a final inspection and we should expect to reject about 0.2% of the assemblies produced.

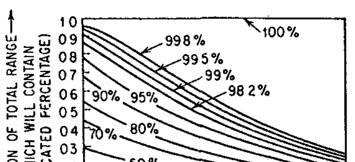

Fig. 4 - The probability distribution of additive tolerances in multiple component assemblies. See text.

Notice that as more and more parts are added to the assembly, the curve in Fig. 3 begins to look more and more like the "normal distribution curve" so beloved of statisticians. Further, if our production process does not produce a uniform distribution (as in Fig. 1), the progression of Fig. 3 can be started at any stage. For example, if the production process produces a triangular distribution for each part (as in Fig. 2), the curve labeled "4" in Fig. 3 would apply to a two-part assembly, "8" to a four-part assembly, and so on. The significance of this is, of course, that most production processes produce a distribution resembling the "normal" curve rather than the rectangular, or uniform distribution of Fig. 1. Thus, the distributions indicated in Figs. 3 and 4 are a relatively conservative evaluation of the usual situation.

It turns out that the statistics of "normal" distributions are such that if some percentage (say X%) of the individual pieces making up an assembly fall within some fraction of their tolerance ranges, then X% of the assemblies will fall within $(1/N)^{\frac{1}{2}}$ of the range sum, where N is the number of pieces making up the assembly. For an assembly of 16 parts $(1/N)^{\frac{1}{2}}$ is 0.25, and if, say 95% of the individual parts fall with a range of ± Y, then 95% of the assemblies should fall within a range of ± 0.25 x 16 x Y = ± 4 Y (rather than the ± 16 Y one might expect).

Happily, we need not concern ourselves with rigorous statistical analysis. A simple expression will allow us to estimate the effect of a combination of a number of tolerances. The expression is the square Root of the Sum of the Squares, which is often abbreviated R.S.S. In our case, the expression takes the form

$$T = \sqrt{\Sigma t_i^2} \qquad (1)$$

where t_i are the effects of the individual tolerances and T is the maximum value that the combination of all the effects will produce. Actually, T is the value that will be exceeded by only a very small fraction of all the assemblies produced. For parts produced to a rectangular or uniform probability distribution (as in Fig. 1), the fraction is about 10%. For a triangular distribution (Fig. 2), the fraction is 1% to 3%. Obviously, the fraction decreases as the individual piece part distribution is more concentrated about the nominal value.

A few numerical examples are instructive. If the individual tolerance on some characteristic produces a change of X, and we have an assembly of n parts, then Eqn. 1 tells us that most assemblies will vary from the nominal by less than

$$T_n = \sqrt{n \cdot X^2} = X\sqrt{n}$$

For an assembly of four parts, n = 4 and T_n = ± 2X, which is just half of the possible total range of ± nX = ± 4X. For an assembly of 16 parts, n = 16 and T_n = ± 4X, just one-quarter of the possible range of ± 16X.

If some tolerances produce larger changes than others, that is, if the tolerance effects are not uniform, Eqn. 1 shows us that the larger effects will dominate the assembly. For example, assume we have 10 tolerances. Nine of them are ± X and the tenth is equal to ± 10X. Then we have

$$T_n = \sqrt{9 \cdot X^2 + (10X)^2} = \sqrt{109\ X^2} = \pm 10.44\ X$$

and we see that the nine tolerances of ± X have increased T_n by only 0.44X from the value of 10 X which would result from the ± 10X tolerance alone.

III ESTABLISHING THE "PERFORMANCE" TOLERANCES

Occasionally, the specification of the "performance" characteristics of an optical system may be directly used as tolerances. For example, the focal length, back focus, vertex length, etc., may be directly specified. However, the image quality aspect of performance is often not as definitively established, and even when it is clearly stated its relationship to the ray aberrations is not as direct as one might wish.

For optical systems which operate with detectors, it is frequently a simple matter to specify the image quality requirement in terms of the percentage of the flux in a point image which falls within some given area. Since such systems often are far from diffraction limited, this performance criterion can be directly related to the calculated geometrical aberrations.

However, for many systems not only must diffraction be accounted for, but image quality or resolution is the performance characteristic which must be maintained. Happily, if we can express the image quality as the Modulation Transfer Factor (MTF) at a given frequency, we can relate it to the wavefront deformation (OPD) caused by the aberrations.

Figure 5 shows the changes in MTF produced by various amounts of defocussing, which is the simplest of all the aberrations. Although the degradation of MTF caused by the various other aberrations is not identical to that due to defocussing, the effects are very similar and, for our purposes, we can use the defocussing relationships as representative of all of the aberrations. Levi and Austing (Ref. 2) published an extensive table of numerical values of the data contained in Fig. 5. Notice that Fig. 5 is normalized so that it can be applied to systems of any Numerical Aperture (or f/#) and wavelength.

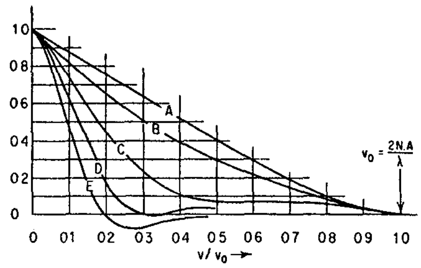

Fig. 5A - The effect of defocussing on the MTF. Curve A, in focus; curve B, 0.25 wave out of focus; C, 0.5 wave; D, 0.75 wave; E, one wave out of focus.

The conventional ray-traced aberrations can be converted to wavefront deformations, or OPD, by the following relationships:

OPD in wavelengths	=	Transverse Spherical	x	$(NA/16\lambda)$	(2)
OPD in wavelengths	=	Tangential Coma	x	$(NA/6\lambda)$	(3)
OPD in wavelengths	=	Defocus or Field Curvature	x	$(NA^2/2\lambda)$	(4)
OPD in wavelengths	=	Longitudinal Chromatic	x	$(NA^2/8\lambda)$	(5)
OPD in wavelengths	=	Lateral Color	x	$(NA/2\lambda)$	(6)

where NA is the numerical aperture, and $NA = 1/(2f/\#)$, and λ is the wavelength.

Thus, the aberrations and the changes in the aberrations can be expressed in waves of OPD, and their effect on the MTF can be forecast from Fig. 5 or its equivalent.

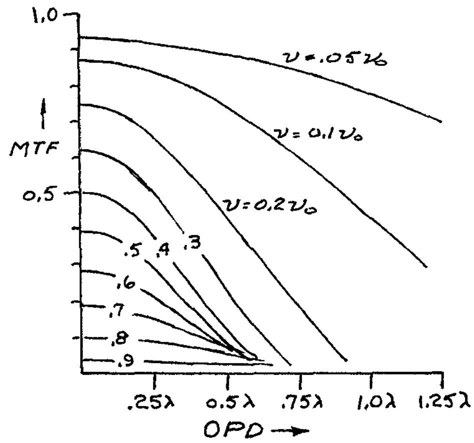

Fig. 5B - The effect of OPD due to defocussing on the MTF for various spatial frequencies, expressed as fractions of the cutoff frequency $\nu_0 = 2NA/\lambda = 1/\lambda\ (f/\#)$.

We can proceed somewhat along the following line if the performance is specified as a certain MTF at a given spatial frequency in lines per millimeter (LPM). The nominal design is analyzed and the MTF at the specified LPM is determined. From Fig. 5, we can determine that this corresponds to the MTF produced by a certain amount of OPD; we will call this OPD (design). Next, again using Fig. 5, we can determine the OPD corresponding to the specification MTF, which we call OPD (spec.). Then the amount of OPD available for the fabrication tolerances is the difference between these two values. The difference can be taken as OPD (tol) = OPD (spec.) - OPD (design); in many instances however, we are justified in assuming that tolerance and design OPD's combine according to the RSS rule, so that

$$\text{OPD (tol)} = \sqrt{\text{OPD(spec)}^2 - \text{OPD (design)}^2}$$

Occasionally performance is specified as a requirement that the MTF at a certain LPM be maintained over some depth of focus. Again the nominal design can be analyzed to determine the MTF which it will maintain over the specified depth; this can be correlated (using Fig. 5) to an OPD. Comparison of this OPD to the amount required to reduce the MTF to the specified level then indicates the difference available for tolerances.

When the image quality is specified by a description of the energy distribution in the (diffraction) image of a point, one can often utilize the Strehl ratio (see Eqn. 8). The Strehl ratio is the intensity of the peak of the diffraction pattern. The relationship between OPD and the enrgy distribution in the diffraction pattern (see, for example, Ref. 1, p. 298) is often useful as well.

Note that the above describes the aberrations in terms of their peak-to-valley (or peak-to-peak) wavefront deformation. Shannon (ref. 3) has discussed the same relationships with respect to the RMS wavefront deformation, which is useful for high-order aberrations and abruptly irregular surface errors. Typically, the relation between peak-to-valley and RMS is that a deformation described as a quarter wave peak-to-valley will be about one-fifteenth or one-twentieth wave RMS. For simple aberrations RMS = (P-V)/3.5. In this article, we use the peak-to-valley measure.

The peak-to-valley OPD produced by a bump or an irregularity (departure from the prescribed surface figure) is given in wavelength units by:

$$OPD = 0.5\ (\#\ FR)(N'-N)(\lambda_t/\lambda_f)\ \text{wavelengths} \qquad (7)$$

where (# FR) is the number of interference fringes departure of the surface from the best fit prescribed surface, (N'-N) is the index difference across the surface, λ_t is the wavelength at which the fringes are measured and λ_f is the wavelength at which the system is used, i.e., the wavelength in which the OPD is reckoned.

TABLE 1 - 14mm NA 0.42 LASER RECORDING LENS

	Radius	Thickness	Glass	Clear Aperture
0	Object	76.539		
1	+50.366	2.80	SF 11	11.65
2	-39.045	.4353	Edge Contact at	11.62
3	-19.836	2.0	SF 11	11.62
4	-34.36	0.2		11.90
5	+17.42	2.65	SF 11	11.81
6	+79.15	11.84		11.22
7	+ 7.08	2.24	SF 11	5.24
8	+15.665	3.182		4.13
9	Plano	2.032	Acrylic	
10	Plano			

NUMERICAL EXAMPLE: The prescription in Table 1 is for a 14mm NA 0.42 laser disk recording lens which operates at 0.82 microns and covers a field of 0.7mm at the short conjugate with a magnification of 0.18X. The specification for this lens is that the peak of the diffraction pattern of the image of a point must be not less than .75 of that of a perfect lens, over the entire field. This is the Strehl ratio; it is related to wavefront distortion by

$$S = (1 - 2\pi^2 w^2)^2 \qquad (8)$$

where w is the RMS wavefront aberration. If we assume that the RMS OPD is approximately equal to 1/3.5 times the peak-to-valley OPD, then the specification of a Strehl ratio of 0.75 corresponds to an OPD of 0.288 waves of peak-to-valley wavefront distortion.

The nominal design has an OPD of .04 waves on axis and an OPD of 0.23 waves at the edge of the field. Using the latter value, we find that if the fabrication tolerances combine to produce an OPD of 0.173 waves, then the RSS sum of design OPD and the tolerance OPD will be just 0.288 wavelengths. Thus our task is to determine a tolerance budget for this lens which will produce no more than 0.173 waves of OPD.

IV CALCULATION OF THE "CHANGE TABLE"

A "change table" is simply a tabulation of the changes in several selected aberrations produced by small changes in the construction parameters of the lens. Such tables can be calculated in several ways. An algebraic calculation of exact partial differentials is possible. Most full scale optical design programs will calculate partial derivatives by changing one parameter at a time by a small amount (an amount to the order of the size of the expected tolerance on that parameter) and calculating the change in the aberrations.

The parameters of the optical system subject to tolerance variation include surface radius and figure, element thickness, airspace , refractive index, chromatic dispersion, and surface tilt (or decentration). The aberrations of interest usually include spherical, coma, astigmatism, Petzval curvature, distortion, longitudinal and lateral chromatic. Focal length, image position, magnification, or similar characteristics are often included as well.

Thus, we arrive at a tabulation of the change in OPD corresponding to the change in each aberration produced by a "tolerance-sized" change in each dimension of the system. Table 2 is the change table for our laser recording lens. Each entry is the OPD change (in peak-to-valley wavelengths) produced by a parameter change of the size indicated. For example, the entry in the first column of the first row indicates that a change of radius #1 corresponding to 10 fringes departure from the nominal test plate radius produces a change in the spherical aberration corresponding to an OPD of .014 wavelength.

TABLE 2 - TABULATION OF THE ABERRATION CHANGE PRODUCED BY PARAMETER CHANGES, IN WAVELENGTHS OF P-V OPD

	TA	$COMA_t$	ASTIG.	RSS	RSS OF CLASS
R1*	+.014λ	+.007λ	+.003λ	.016λ	
R2*	-.005	-.020	-.002	.021	
R3*	-.051	+.027	-.005	.058	Radius
R4*	+.017	-.021	-.005	.027	.101λ
R5*	-.027	-.010	+.002	.029	
R6*	+.028	-.006	-.003	.029	
R7*	-.013	+.004	+.003	.014	
R8*	+.057	+.017	-.005	.060	
T1**	-.001λ	+.003λ	+.002λ	.004λ	
T2**	-.020	+.029	+.000	.035	Thickness
T3**	-.037	-.004	+.003	.037	.091λ
T4**	+.017	-.021	+.002	.027	
T5**	+.021	-.029	+.005	.036	
T6**	+.037	-.044	+.008	.059	
T7**	-.008	-.009	+.002	.012	
N1***	+.007λ	.000λ	-.004λ	.008λ	
N3***	+.002	.000	-.003	.004	Index
N5***	-.005	.000	.000	.005	.011λ
N7***	-.004	.000	.000	.004	
TR1****	---	+.043λ	+.009λ	.044λ	
TR2****	---	-.069	+.010	.070	
TR3****	---	+.179	-.015	.180	
TR4****	---	-.093	+.009	.093	Tilt
TR5****	---	+.101	+.013	.102	.277λ
TR6****	---	-.106	+.006	.106	
TR7****	---	+.024	-.014	.028	
TR8****	---	-.080	+.010	.081	
RSS TOTAL	.110λ	.286λ	.034λ	.308λ	.308λ

R* Change of radius corresponding to 10 fringes (rings) departure from the nominal test plate radius (see Ref. 1, p. 412).

T** Change of thickness or airspace of 0.2mm.

N*** Change of index of .001.

TR**** Tilt of surface of 0.001 radians (3.4 minutes).

A surface irregularity (asphericity) of one fringe produces an OPD of

$$OPD = 0.5\ (1)\ (1.764-1)(.59/.82) = .275$$

per surface according to Eqn. 7, for an index of 1.764 if we assume a test wavelength of 0.59 microns (Sodium-D) and an operating wavelength of 0.82 microns. Since there are eight surfaces, the RSS summation is the square root of eight (2.83) times this amount. Thus the probable OPD introduced by one fringe of irregularity on each surface is 2.83 times 0.275, or 0.778 waves.

The table has been limited to 3 aberrations, Transverse Spherical Aberration (TA), Tangential Coma ($COMA_t$), and Astigmatism. This is done for two reasons: 1) to simplify and condense our discussions and 2) because in this example these are the predominant factors affecting the image quality. This latter situation is very often the case. One can markedly reduce the labor and complexity of the tolerancing task without affecting its accuracy or value, by dropping from consideration those aberrations whose changes are small in comparison with the others. This is, of course, justified by the numerical analysis in the last paragraph of Section II above. Note that for most optical systems the tangential field curvature (X_t) would be used rather than the astigmatism. In this particular application, the lens is refocussed if the laser spot image is moved off-axis, and the field curvature is effectively cancelled out by the refocussing.

V THE TRIAL TOLERANCE BUDGET

The next step is to assume a preliminary set of tolerances which seems reasonable. Table 3 is a rough indication of what might be considered as "typical" optical tolerances. In the absence of other information, it can serve as the source for a preliminary tolerance budget.

TABLE 3 - TYPICAL OPTICAL SHOP TOLERANCE

	Radius	Regularity	Thickness	Index	Surface Tilt
Low Cost	50 rings	10 rings	0.5mm	.002	.005 radian
Commercial	10 rings	2 rings	0.2mm	.002	.001
Precision	5 rings	1 ring	0.1mm	.001	.0003
Extra Precise	1 ring	.25 ring	0.05mm	.0002	.0001

For our numerical example, we can begin by assuming that the changes used in Table 2 are an appropriate starting point for our tolerance budget. If we take the RSS of all the changes in the Transverse Spherical Aberration (TA), we obtain .110 waves. Similarly, for $Coma_t$ we get $.286\lambda$, and for Astigmatism we get $.034\lambda$. We now take the RSS over the three aberrations and find that we can expect a variation of about $.308\lambda$ in the OPD resulting from our preliminary tolerance budget. If we include one fringe of irregularity, the total variation becomes 0.84 waves of OPD (RSS $.309\lambda$ with $.778\lambda$ to get the .84 sum).

VI ADJUSTING THE TOLERANCE BUDGET

The OPD of 0.84 wavelengths exceeds the value of .288 which we determined in Section III to be the maximum which we could allow in order to maintain the Strehl ratio of 0.75. Since it is too large by a factor of .84/.288 = 2.9X, we could simply reduce our trial budget by this factor across the board. This is usually not the best way.

An inspection of Table 2 and its footnotes indicates that the sensitivity of the tolerances varies widely, ranging from the total insensitivity of coma to the indicated index changes, to significant effects from the radius and thickness changes and very heavy contributions from the assumed surface tilts (or decentrations).

We have previously (in the last paragraph of Section II) noted that the RSS process indicates that the larger tolerance effects are much more significant than the smaller; the significance varies as the square of the size. Thus, a rational approach is to reduce the tolerances on those parameters which are the most sensitive. conversely, one might also consider increasing the tolerances on those parameters which are relatively insensitive.

This is the technique which we shall apply here. However, there are practical considerations which should be observed. In most optical shops there is a fairly standard tolerance profile. For example, a shop may do most of its work to a five ring test glass fit, a thickness tolerance of ± 0.1mm, and centering to a one minute deviation. If a larger tolerance is allowed, there will be a saving, but it will not be proportional to the increase in the tolerance. This is because the shop will still tend to produce to its customary profile. They may be able to relax their procedures a bit, and their usual percentage of rejections will drop, but the tendency will be very strong to produce the usual profile whether it has been specified or not. Thus, there is a limit on the increase in tolerance size which will produce a real savings. As another example, many optical glasses are routinely produced to an index tolerance of ± .001 or ± .0015. There is no saving in cost if the tolerance is increased beyond the standard commercial tolerance.

When tolerances are reduced below the "standard profile" however, the cost of fabrication begins to climb. This results from the additional care and effort necessary to hold the tighter tolerances and/or an increase in the rejection rate. In most shops there is effectively a practical limit to the smallness of a given class of tolerance, since the cost of fabrication rises asymptotically toward infinity as this limit is approached.

Thus, for most shops there is both a high limit on tolerances, beyond which there is no savings, and a low limit, which the shop is barely capable of meeting. Obviously, one should confine the tolerance specifications to this range (or find another shop whose capabilities encompass one's requirements).

If we take the RSS of the contributions of each parameter tolerance individually, as we have done in the last column of Table 2, then we get a convenient measure of the sensitivity of each tolerance. Examination of the table indicates that the variations of radius, thickness, index and especially surface tilt are all significant contributors to the final RSS OPD. If there are a few very large contributors, a possible general technique would be to reduce any dominant tolerances by a factor approximating the factor by which the OPD of trial budget exceeds the acceptable OPD. Another technique is to make the tolerance size inversely proportional to its sensitivity, so that each tolerance produces the same OPD; this is obviously subject to the limitations outlined above, as well as the necessity to weigh each class of tolerance in some way so as to take into account their different natures and costs.

Following this line, we get the following budget, for which the RSS OPD is 0.167λ, just slightly better than the 0.173λ required for our Strehl ratio specification of 75%.

TABLE 4 - FINAL OPTICAL TOLERANCE BUDGET

Tolerance			P-V RSS OPD
Radius test plate fit	:	1 Ring	.010 λ
Surface regularity	:	1/5 Ring	.156
Index variation	:	.001	.011
Surface tilt	:	.0002 Radians	.055
Thickness tolerance	T1:	0.10	.002
	T2:	0.02	.004
	T3:	0.05	.009
	T4:	0.04	.005
	T5:	0.05	.009
	T6:	0.03	.009
	T7:	0.07	.004
		RSS Total	.167 λ
		Edge of Field Design	.23λ
		RSS Total	.284λ

$$\text{Strehl Ratio} = (1 - 2\pi^2(.282/3.5)^2)^2 = 0.757$$

VII CONCLUSION

We have outlined a relatively simple and straightforward technique for the establishment of a performance-determined tolerance budget. A numerical example was worked out, and a budget was determined which corresponded to a specified image quality level.

This technique has been used by the author for many years and has been applied to a wide variety of optical systems. It has been applied to fabrication quantities ranging from thousands down to lots of one or two. It has yet to fail. (This may indicate that it errs on the conservative side.)

There exist more elegant and more "automatic" methods of accomplishing this task. For example, see Ref. 4. However, our primary aim here is to establish an understanding of optical tolerancing and of the basic methods which can be used to solve the fundamental problem of arriving at a useful optical tolerance budget.

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