9 Tolerance Analysis

9.1 SOME GENERAL TOPICS ABOUT TOLERANCE

9.1.1 What is Tolerance Analysis?

Nothing is perfect in the world. A real lens element fabricated is more or less different from the designed element in terms of surface radius and smoothness, central thickness, parallelism between the two surfaces, and glass index and Abbe number. In addition, an element will not be perfectly mounted; there is always a centering error, a position error and a tilting error. Because of all these errors, the performance of a real lens will be more or less lower than the design performance. Tolerance analysis is meant to set the maximum acceptable range for every error so that the lens can still perform to the specifications.

Lens element fabrication technique determines the achievable element tolerance. H. H. Karow's book, *Fabrication Methods for Precision Optics* (Wiley, New York City, 1993), is probably the most referred book about lens fabrication.

9.1.2 Some Simple Examples of Element Mounting Error Affects Performance

All the fabrication and mounting errors affect the performance of a lens in an accumulative way. But some lens elements are more sensitive to the errors than other lens elements. Figure 9.1 shows some examples. The two elements shown in Figure 9.1a have the same magnitude of decentering d from the optical axis, the top element has smaller surface radius, and the decentering more severely deflects the horizontal incident ray than the bottom element does. The two elements shown in Figure 9.1b and c have the same magnitude of axial position error t, the element in (b) has shorter surface radius, and the position error more severely deflects the incident ray than the element in Figure 9.1c does. Generally speaking, elements with short surface radii or with large incident/exit ray angles are more sensitive to fabrication and mounting errors. A lens with many short radius elements and large incident/exit ray angles may perform well on paper, but difficult to assemble.

9.1.3 Element Surface Decentering and Wedge

For a spherical element, decentering and tilt between the two surfaces are actually the same thing. Figure 9.2 shows an exaggerated example. The two surfaces of an element are decentered with a magnitude d as shown in Figure 9.2a. After we trim the edges of the two surfaces to make an element, we can see that the two surfaces have a wedge angle θ in between them as shown in Figure 9.2b. When we perform tolerance analysis, we only need to analyze either one of these two errors. For an

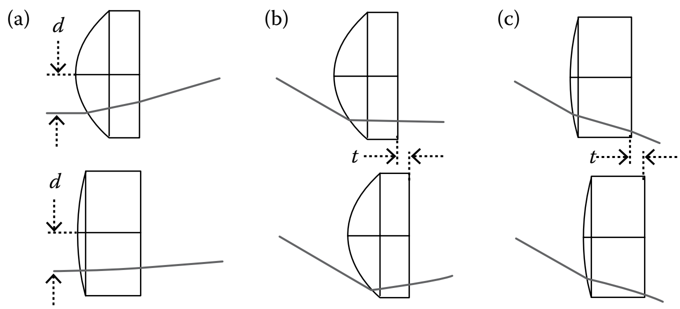


FIGURE 9.1 Some simple examples of element position errors affecting performance. (a) The top element has shorter surface radius and is more sensitive to decentering than the bottom element. The element in (b) has shorter surface radius than the element in (c) and is more sensitive to axial position error.

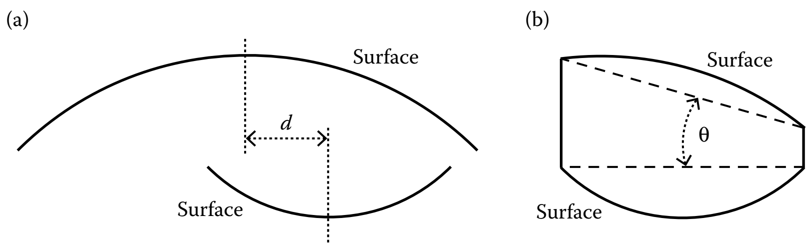


FIGURE 9.2 For a spherical element, decentering between two surfaces is equivalent to a wedge between the two surfaces.

aspheric element, the decentering and wedge between the two surfaces are not necessary the same thing. Tolerance analysis will be more complex.

Note that the decentering and wedge discussed above are between the two surfaces of the same element. These two errors are fabrication errors and are independent of the element mounting errors.

9.1.4 Radius Tolerance: Fringes versus Radius Percentage

The element surface radius tolerance can be specified by either fringes or radius percentage. These two are related by the nonlinear relationship

$$\text{Fringes} = \frac{\Delta Sag}{(\lambda/2)} = \frac{1}{(\lambda/2)8}\frac{D^2}{r}\frac{\Delta r}{r} \tag{9.1}$$

where ΔSag is the element sag tolerance, λ is the test laser wavelength, D is the element diameter, r is the element radius, and Δr is the radius tolerance. Fringes can be directly measured using a test plate. If the surface irregularity is 1 wave, we need at least two fringes for measurement. Radius tolerance cannot be directly measured, and it has to be calculated from the fringes using Equation 9.1. For a given percentage radius tolerance $\Delta r/r$, the fringes can be below 1 and cannot be measured, if the radius r is very large. Therefore, it's more convenient to use fringes to specify the radius tolerance, although radius percentage tolerance is also widely used. For a flat surface, the radius is infinity, and we have to use fringes to tolerance.

9.1.5 Total Indicator Runout

Total indicator runout (TIR) is a widely used concept to describe the status of an element surface. Figure 9.3 shows an example greatly exaggerated for clarity. The element has a fabrication wedge and is mounted with decentering and tilt. The angle between element surface normal and the optical axis of the lens is the combined consequences of all these three tolerances and is called TIR, as shown in Figure 9.3. Once the three tolerance ranges are set, the TIR range is also determined. On the other hand, the TIR is the one affecting the lens performance. If the TIR is kept within the tolerance range, we don't need to care about the element surface wedge, and the mounting decentering and tilt.

The commonly used technique to control the TIR during element mounting process is the following:

The lens is mounted on a rotatable stage. The mechanical axis of the lens's housing is the lens's optical axis and is aligned with the rotation axis of the stage. An element is placed at its seat and the lens housing with the element in it is being rotated. A laser beam propagates along the optical/mechanical/rotation axis through the lens. The reflected

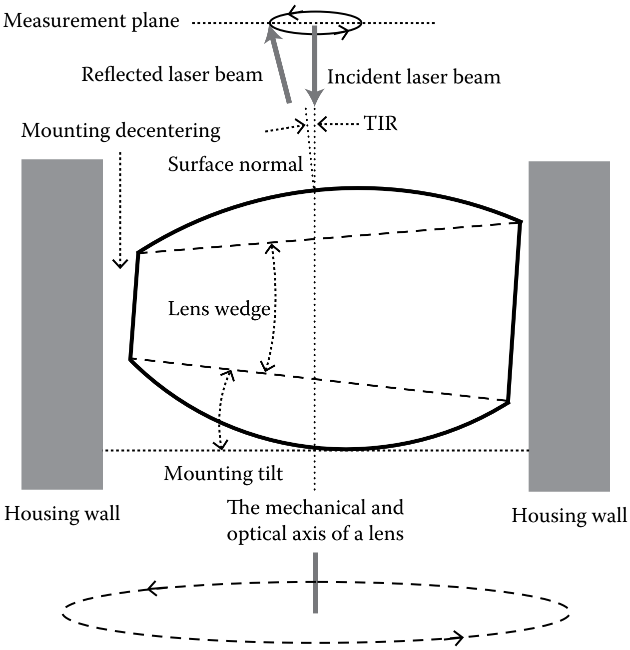


FIGURE 9.3 Illustration of the concept of total indicator run out and the technique to measure and reduce the TIR.

beam spot from the element surface marks a circle because of the TIR as shown in Figure 9.3. The TIR can be calculated by a specially developed software using the circle radius and the distance between the measurement plane and the element surface. As the lens housing is rotating, the lens assembler gently touches the element trying to reduce the radius of the circle the reflected beam spot is marking, till the TIR falls within the specifications. Then the element position is fixed, usually first by UV fast cure adhesive for temporary fixing, and then by some other adhesive for permanent fixing.

9.1.6 Fit Glass Melt Data

9.1.6.1 Glass Data Tolerance Issues

The index and Abbe number tolerance of glasses can usually be controlled to within ±0.001 and ±1% (or ±0.8%), respectively, for commercial grade glass and to ±0.0005 and ±0.5%, respectively, for precision grade glass. Such tolerances are good enough for most lenses. Some high-performance lenses may require tighter glass tolerance. Glass vendors are unlikely to change their manufacturing process to further reduce glass tolerance for us, unless we will buy a large amount of glass. The common way to solve this problem is to modify the lens design for a specific glass production. The steps in this process are as follows:

1. Reserve enough glass supply from a glass vendor or distributor. Lens manufacturers can often do this for us too. Obtain the measured index and Abbe number for the glasses reserved by us; these data are often called “melt data.” Glass vendors should provide these data. Note that this glass melt data may be out of the tolerance range acceptable by the lens being designed.
2. Since all glass models use the nominal glass data, we need to build new glass models using the “melt data.”
3. Reoptimize the lens design using the new glass models. This optimization will be a fast local optimization. The radii and positions of several or all the lens elements may be slightly changed.
4. Have the reoptimized lens elements fabricated using the reserved glasses.
5. Design the lens housing based on the reoptimized lens element shapes and positions.

If we plan to build the lens only once, this “fit glass melt data” approach is appropriate. If we want to repeatedly build many such lenses over a long period of time, we will have a big trouble, because the glass data for next production is very likely different, and we need to reoptimize the lens’s element shapes and positions every time we order new glasses and modify the lens housing and all the drawings accordingly. It’s a nightmare from a production point of view. So, when performing tolerance analysis, we should try to avoid tightening glass tolerance to “melt data” level, rather use more elements with standard glass tolerance.

9.1.6.2 Build New Glass Models Using the Melt Data

If we do have to build new glass models for the melt data, the process is called “fit melt data.” The steps to do it are the following:

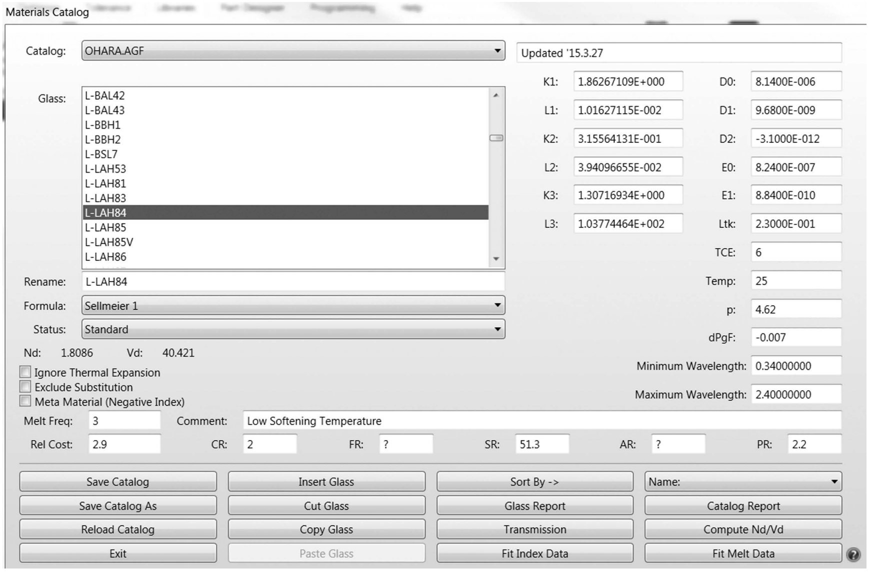


FIGURE 9.4 A *Material Catalog* box.

1. Clicking *Library/Material Catalog*, we can open a *Material Catalog* box, as shown in Figure 9.4. We can select the glass brand in the *Catalog* box, for example, Ohara is selected in Figure 9.4. Highlight any glass as shown in Figure 9.4, and we can see many useful data about this glass.
2. Save the glass catalog under another name, because Zemax is frequently updated. Every time during the update, all the glass catalogs supplied by Zemax will be updated. If we don't save our glass catalog with another name, it will be updated sooner or later and we will lose our glass data.
3. Clicking *Fit Index Data* button, we can open a *Fit Index Data* box, as shown in Figure 9.5, where we can type in the data pair of wavelengths and indexes provided by the melt data.
4. Choose the formula used to fit the index in the *Formula* box. Any formula there will work fine for us.
5. Type in a new glass name in the *Name* box. The new glass name should be related to its original name. For example, if the original glass is N-BK7, we may want to name the fit melt glass like N-BK7_melt_2016.xx.yy.
6. Click *Fit Index Data* button, and then click *Add To Catalog*. The new glass will be added to the current glass catalog, and we are done.

9.1.7 Compensator

Many lenses form an image. The main effect of all these tolerance adding up is defocusing. That means the image plane position will be moved. During the test stage of an image lens, the sensor is often moved back and forth about its design position to find the best focused image, or in another term to compensate for the defocusing.

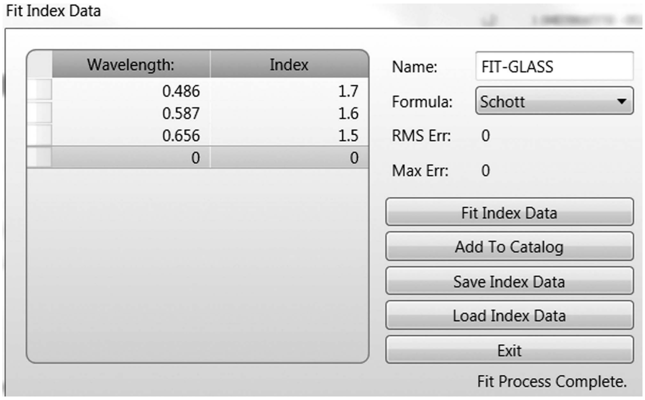


FIGURE 9.5 A *Fit Index Data* box.

When designing a lens without optical power, we often use a paraxial (ideal) lens to form an image. Therefore, in most design cases, there is an image plane that can be used as the compensator.

There are other ways to compensate for the tolerance-caused defocusing, for example, changing the spacing between two lens elements, etc. Zemax tolerance analysis can simulate this test process. When constructing the tolerance data, we need to specify a *Surface* as the "Compensator."

9.1.8 Error Distribution

Most tolerance errors are random numbers, but they obey a distribution pattern. The most commonly seen error distribution pattern is Gaussian or normal distribution described in the following equation:

$$E(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(x-a)^2}{2\sigma^2}\right] \tag{9.2}$$

where x is the error value, a is the mean value of the error, and σ is the standard deviation of the error pattern. The term $1/(2\pi\sigma^2)^{0.5}$ is a normalizing factor coming from

$$\int_{-\infty}^{\infty} E(x)\mathrm{d}x = 1 \tag{9.3}$$

For example, if we have a 10 mm thickness lens element and specify the thickness tolerance range as ±0.1 mm, we have a = 10 mm and σ = 1 mm. Figure 9.6 plots such a normal distribution. The chance that the error falls within plus/minus one standard deviation is 68.3%.

We can select *Uniform* or *Parabolic* error distributions offered by Zemax, if one of these two distributions better describe the real error distribution pattern, but this situation is rare.

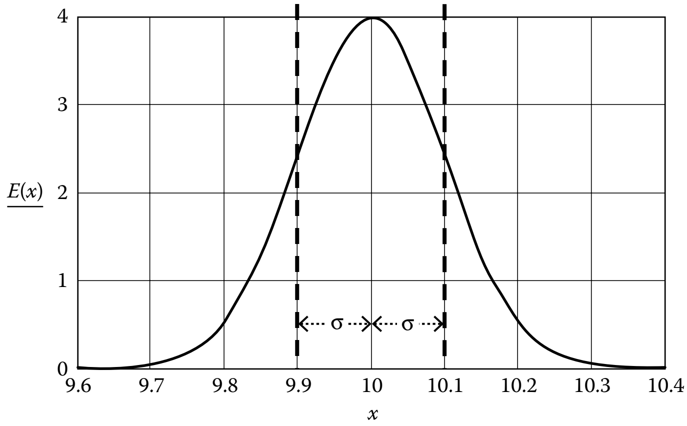


FIGURE 9.6 A Gaussian or normal distribution. The area within plus and minus one standard deviation is 68.3%.

9.1.9 Monte Carlo Analysis

Since all the tolerance errors are statistic, the tolerance analysis is done mainly using Monte Carlo analysis. When performing one Monte Carlo analysis, Zemax generates a set of random error numbers for all the tolerances based on the tolerance ranges set in the *Tolerance Data Editor* box and the error distribution pattern selected by us, then runs raytracing to find the lens performance, usually in term of *RMS Wavefront* error. Since all the error numbers generated are random, the result of every Monte Carlo analysis is different. We need to run Monte Carlo analysis many times to make the results have a statistical meaning. For 100 times of Monte Carlo analysis, the statistics will include a 90% probability result and a 10% probability result. If we run Monte Carlo analysis 1000 times, the statistics will include 98% and 2% probability results.

9.2 CONSTRUCT *TOLERANCE DATA EDITOR* BOX

We use the double Gauss lens shown in Figure 4.1 as an example for illustration. The *Lens Data* box of the double Gauss lens is shown in Figure 9.7.

Clicking *Tolerance/Tolerance Data Editor*, we can open a *Tolerance Data Editor* box. There are over 30 tolerance operands available. Each operand controls one tolerance. We can manually type in the required operands and set the tolerance range in the *Tolerance Data Editor* box. However, this is not the easy way, because we may miss some operands. The easier way is to use *Tolerance Wizard* to construct the *Tolerance Data Editor* box.

9.2.1 Set *Tolerance Wizard* Box

Clicking the "\/" sign at the top-left corner of the *Tolerance Data Editor* box, and then clicking *Tolerance Wizard*, we can open the *Tolerance Wizard* box as shown in Figure 9.8. We can set tolerance range for each type tolerance (not each tolerance).

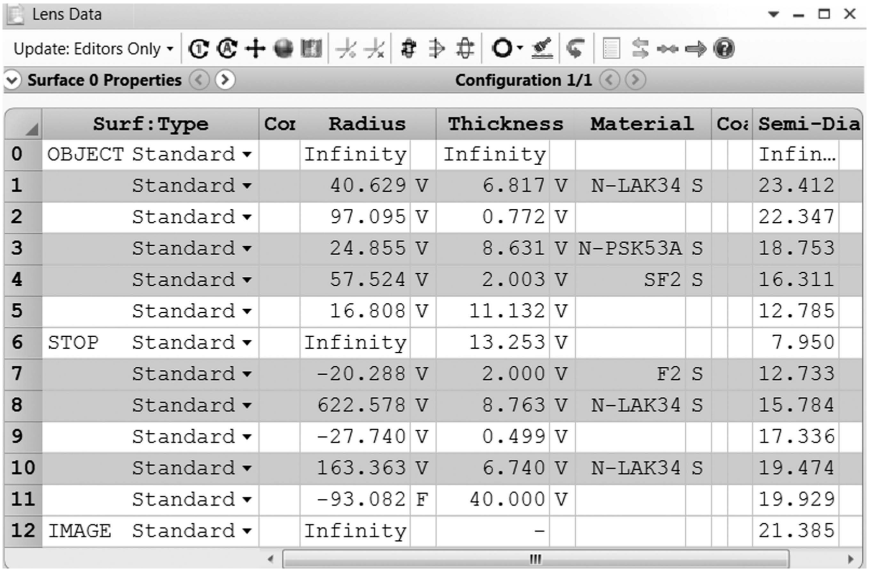


FIGURE 9.7 The *Lens Data* box for the double Gauss lens shown in Figure 4.1.

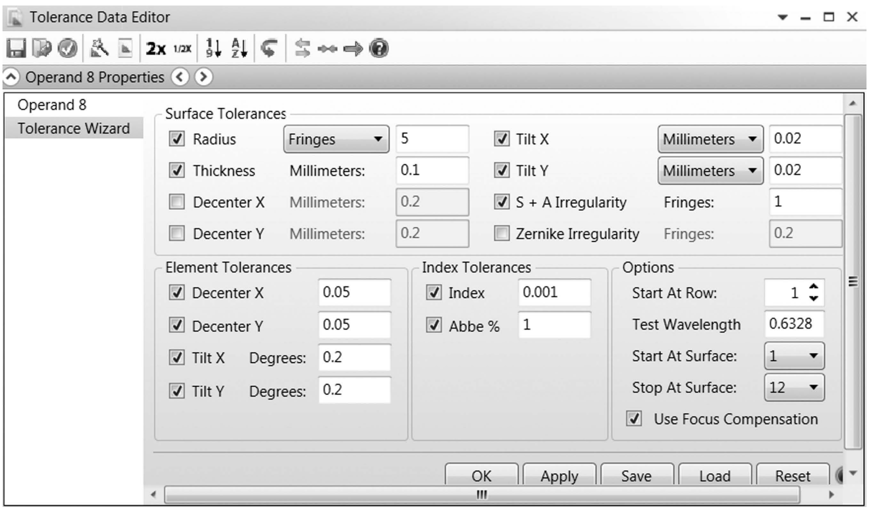


FIGURE 9.8 Set a *Tolerance Wizard* box.

The best way is to start with loose tolerance ranges. If the results of the Monte Carlo analysis show that the lens performance is not good enough with such a tolerance set, we can gradually tighten the ranges of these tolerances that make big contributions to the drop in the lens performance. This approach can avoid overtightening the tolerances. Below we explain how to set the *Tolerance Wizard* box.

9.2.1.1 Element Fabrication Tolerance

The upper half of the box is for *Surface Tolerances*, which is about lens fabrication tolerances. Below we explain item by item how to set the lens fabrication tolerance.

1. *Radius*. We can select either tolerance with unit *Millimeters* or tolerance with unit *Fringes*. The problem of using radius tolerance is that most lens elements have different radii. The tolerances millimeter units must be different for most elements, and we need to type in all these different radius tolerances for every element in the *Tolerance Data Editor* box, which is not convenient. While using surface curvature tolerance, we can type in one fringe number in the *Tolerance Wizard* box for all the surfaces. Here we type in 5.
2. *Thickness*. The commonly used thickness tolerance is ±0.05 mm; we type in 0.1 (mm) here as a starting point.
3. *Decenter X* and *Decenter Y*. As we explained in Section 9.1.3, the lens surface decenter is equivalent to the surface tilt (wedge). We don't need to include double tolerance for them. Since surface decenter is more difficult to measure than surface tilt, we uncheck these two boxes.
4. *Tilt X* and *Tilt Y*. These two are equivalent to *Decenter X* and *Decenter Y*. Either sag difference with the unit *Millimeter* or wedge angle with the unit *Degree* can be used. But sag difference is the one that can be directly measured and controlled. A wedge angle needs to be calculated using sag difference and the lens diameter. For a large lens, a given wedge angle means a large sag difference and can be easy to achieve while the same wedge angle may be difficult to achieve for a small lens. So, we select *Millimeter*. The commonly used sag difference tolerance is ±0.01 mm, so we type in ±0.02 mm.
5. *S + A Irregularity*. A 0.5 wave is common for lens surface irregularity. We type in 1 wave.
6. *Zernike Irregularity*. It's redundant since we have selected *S + A Irregularity*.

9.2.1.2 Element Mounting Tolerance

The *Element Tolerance* at the lower half of the *Tolerance Wizard* box is for lens mounting tolerance.

1. *Decenter X* and *Decenter Y*. The decenter and tilt of lens mounting are two different issues. We need to specify both the tolerances. Mounting tolerance of the lens can vary highly, based on lens housing the structure and the mounting technique used. We type in 0.05 (mm).
2. *Tilt X* and *Tilt Y*. We type in 0.2 (degree).

9.2.1.3 Other Tolerances and Related Issues

The *Index Tolerances* are for glasses.

1. Type the commonly used glass index tolerance of 0.001 in the *Index* box.
2. Type the commonly used Abbe number tolerance of 1% in *Abbe%* box.

Other tolerance related issues are as follows:

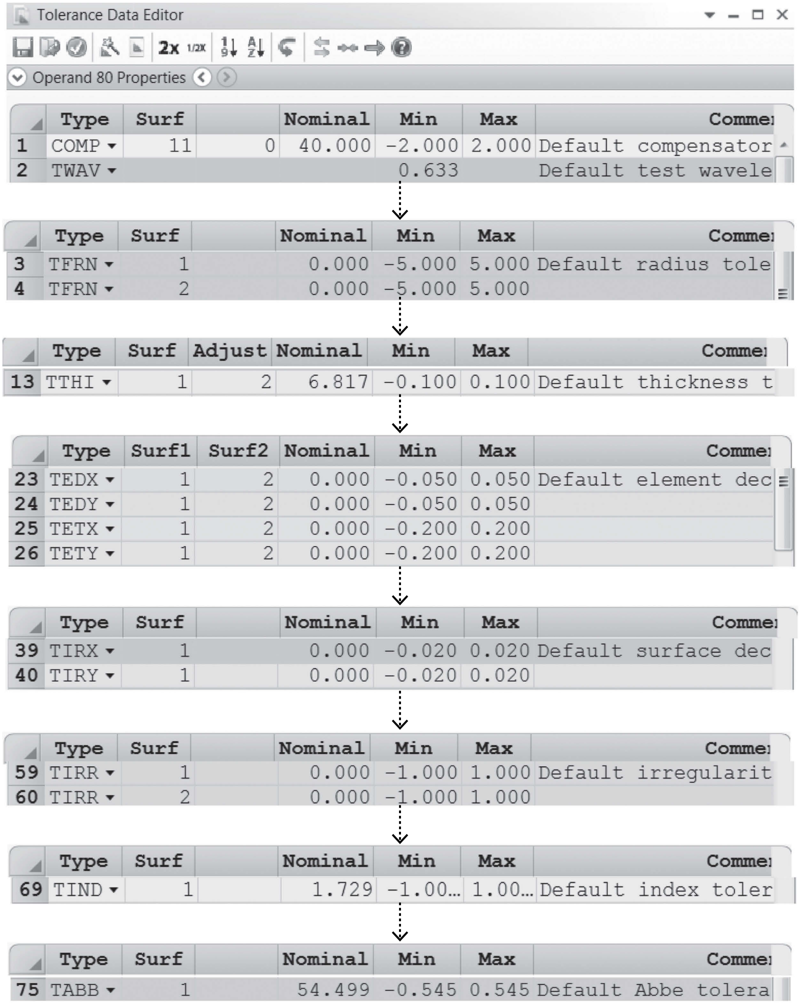
1. *Start at Row*. Select 1 if there is no other content in the *Tolerance Data Editor* box.
2. *Test Wavelength*. He–Ne laser is commonly used to test lenses, and the wavelength is 0.6328 μm.
3. *Start At Surface* and *Stop At Surface*. Select the range of surface in the *Lens Data Editor* box to perform the tolerance analysis. If nothing special is going on, the range should cover all the elements. That is from surface 1 to surface 12 for the double Gauss lens.
4. We should check the *Use Focus Compensation* box so that Zemax will move the image plane back and forth during the tolerance analysis process for the best focusing.

After the abovedescribed steps are completed, the *Tolerance Wizard* box should look like that shown in Figure 9.8. Click *OK* to close it and the *Tolerance Data Editor* box will be automatically updated. Zemax will select all the right operands for us based on the the *Tolerance Wizard* box and the *Lens Data* box.

9.2.2 *Tolerance Data Editor* Box

Figure 9.9 shows several portions of the *Tolerance Data Editor* box we have obtained. Below we explain the box row by row.

1. Row 1 *Comp*. Specify the compensator. The surface number is the image surface number in most cases. If we will compensate for the tolerance caused defocusing by changing the spacing between two other surfaces, we need to change the *Comp* surface number. The *Nominal* in this case is the distance between the image surface and the surface ahead. *Min* and *Max* define the range the image surface is allowed to move. For example, if the lens housing has a room and mechanism for the sensor to move ±10 mm, we should type in −10 and 10 in the *Min* and *Max* boxes, respectively.
2. Row 2 *TWAV*. This is the wavelength of testing the lenses, and we can change this number.
3. Rows 3 and 4 *TFRN*. The radius tolerance in fringes.
4. Rows 13 and 14 *TTHI*. The thickness tolerance starts at row 13. We already typed in 0.1 (mm) in the *Tolerance Wizard* box. The *Adjust* column is a little complex, and we devote Section 9.2.3 to explain this issue. We don't need to touch the *Adjust* column here since Zemax has already set these for us. That is one of the advantages of using *Tolerance Wizard* box. There are many *TTHI* rows to handle the thickness tolerance of other surfaces. We skip the details here.
5. Rows 23 and 24 *TEDX* and *TEDY*. Element (lens) centering tolerance in x and y directions, respectively. This is the lens mounting tolerance. We already typed in 0.05 (mm) in the *Tolerance Wizard* box. There are many *TEDX* and *TEDY* rows to handle the centering tolerance of other elements. We skip the details here.



	Type	Surf		Nominal	Min	Max	Comme
1	COMP	11	0	40.000	-2.000	2.000	Default compensator
2	TWAV				0.633		Default test wavele

	Type	Surf		Nominal	Min	Max	Comme
3	TFRN	1		0.000	-5.000	5.000	Default radius tole
4	TFRN	2		0.000	-5.000	5.000	

	Type	Surf	Adjust	Nominal	Min	Max	Comme
13	TTHI	1	2	6.817	-0.100	0.100	Default thickness t

	Type	Surf1	Surf2	Nominal	Min	Max	Comme
23	TEDX	1	2	0.000	-0.050	0.050	Default element dec
24	TEDY	1	2	0.000	-0.050	0.050	
25	TETX	1	2	0.000	-0.200	0.200	
26	TETY	1	2	0.000	-0.200	0.200	

	Type	Surf		Nominal	Min	Max	Comme
39	TIRX	1		0.000	-0.020	0.020	Default surface dec
40	TIRY	1		0.000	-0.020	0.020	

	Type	Surf		Nominal	Min	Max	Comme
59	TIRR	1		0.000	-1.000	1.000	Default irregularit
60	TIRR	2		0.000	-1.000	1.000	

	Type	Surf		Nominal	Min	Max	Comme
69	TIND	1		1.729	-1.00...	1.00...	Default index toler

	Type	Surf		Nominal	Min	Max	Comme
75	TABB	1		54.499	-0.545	0.545	Default Abbe tolera

FIGURE 9.9 Some portions of the *Tolerance Data Editor* box for the double Gauss lens.

6. Rows 25 and 26 *TETX* and *TETY*. Element (lens) tilt tolerance in degree in *x* and *y* directions, respectively. This is the lens mounting tolerance. We already typed in 0.2 (degree) in the *Tolerance Wizard* box. There are many *TETX* and *TETY* rows to handle the tilt tolerance of other lenses. We skip the details here.
7. Rows 39 and 40 *TIRX* and *TIRY*. Surface tilt tolerance in *x* and *y* directions, respectively. This is the lens fabrication tolerance. We already typed in 0.02 mm in the *Tolerance Wizard* box. There are many *TIRX* and *TIRY* rows to handle the surface decenter tolerance of other lens surfaces. We skip these details here.

8. Row 59 *TIRR*. Surface irregularity tolerance. We already typed in 1 (wave) in the *Tolerance Wizard* box. There are many *TIRR* rows to handle the surface irregularity tolerance of other lens surfaces. We skip the details here.
9. Row 69 *TIND*. Glass index tolerance. We already typed in 0.0001 in the *Tolerance Wizard* box. There are many *TIND* rows to handle the index tolerance of other glasses. We skip the details here.
10. Row 75 *TABB*. Glass Abbe number tolerance. We already type in 1 (%) in the *Tolerance Wizard* box. There are many *TABB* rows to handle the Abbe number tolerance of other glasses. We skip the details here.

Note that the tolerance range does not have to be symmetric. For example, if a lens thickness is 10 mm + 0.3 mm/ – 0.5 mm, Zemax will treat this as thickness of 9.9 mm ± 0.4 mm.

With the *Tolerance Data Editor* box being set, we are ready to run tolerance analysis.

9.2.3 Explain the *Adjust* in *Thickness Tolerance*

9.2.3.1 Three Examples

The *Adjust* in *Tolerance Data Editor* box deserves some special explanation. Figure 9.10a shows a case with two single elements. If the thickness of surface N has a tolerance that moves surface $N+1$, surface $N+2$ is not moved. That means the thickness of surface $N+1$ needs to be adjusted to compensate for the thickness change of surface N; therefore surface $N+1$ is the *Adjust* for surface N. For the thickness tolerance of surface $N+1$, there will be another *Adjust*. In most cases, Zemax will select the right *Adjust* for every thickness tolerance and do these adjustments during the tolerance analysis process. That is another advantage of using *Optimization Wizard Tolerance* box to set the *Tolerance Data Editor* box.

Figure 9.10b shows a case with a doublet and a singlet. If the thickness of surface N has a tolerance, both surface $N+1$ and $N+2$ are moved, but surface $N+3$ is not moved. That means the thickness of surface $N+2$ is adjusted to compensate for the thickness change of surface N. Figure 9.10c shows another example with three single elements. The position of the middle element is determined by a spacer between the middle element and the left side element. If the thickness of surface N has a tolerance that moves surface $N+1$, the spacer, surfaces $N+2$ and $N+3$ are also moved. But surface $N+4$ is not moved. That means surface $N+3$ is the *Adjust*.

9.2.3.2 Zemax Cannot Take Care of the Effect of Mechanical Structure

When *Optimization Wizard Tolerance* box is used to construct the tolerance data, Zemax will select the right *Adjust* for us based on the *Lens Data* box. That means Zemax will take care of the cases shown in Figure 9.10a and b. But the *Lens Data* box does not contain the mounting information such as the spacer shown in Figure 9.10c. Zemax will not change the *Adjust* accordingly, therefore we have to manually select the *Adjust*.

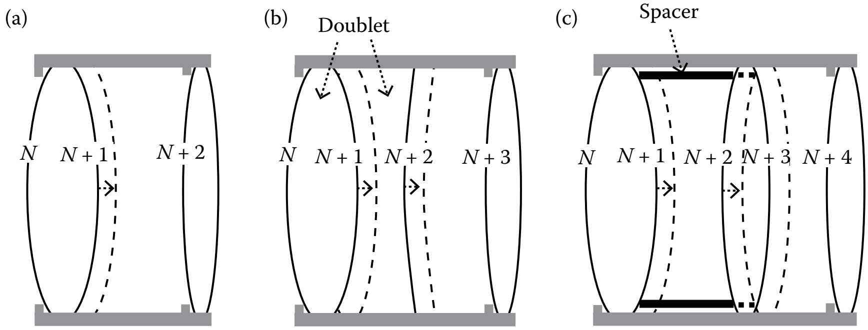


FIGURE 9.10 Illustration of *Adjust* in thickness tolerancing. (a) Two single elements case. When surface *N* has a thickness tolerance, surface *N* + 1 is the *Adjust*, and surface *N* + 2 does not move. (b) One doublet one singlet case. When surface *N* has a thickness tolerance, surface *N* + 2 is the *Adjust*, and surface *N* + 3 does not move. (c) Three single elements with a spacer in between the first two elements. When surface *N* has a thickness tolerance, surface *N* + 3 is the *Adjust*, and surface *N* + 4 does not move.

9.3 TOLERANCING

9.3.1 Set *Tolerancing* Box and Perform Tolerancing

After completing the *Tolerance Data Editor* box, we need to set the *Tolerancing* box by clicking *Tolerance/Tolerancing* to open a *Tolerancing* box. There are four buttons in the box. Shown in Figure 9.11 is the *Tolerancing* box with the *Criterion* button clicked. The process of setting the *Tolerancing* box is described below:

1. Click the *Set-Up* button and select *Sensitivity* that is the commonly used one. The *Force Ray Aiming On* box should be checked for more accurate result. The other selections do not make much difference.

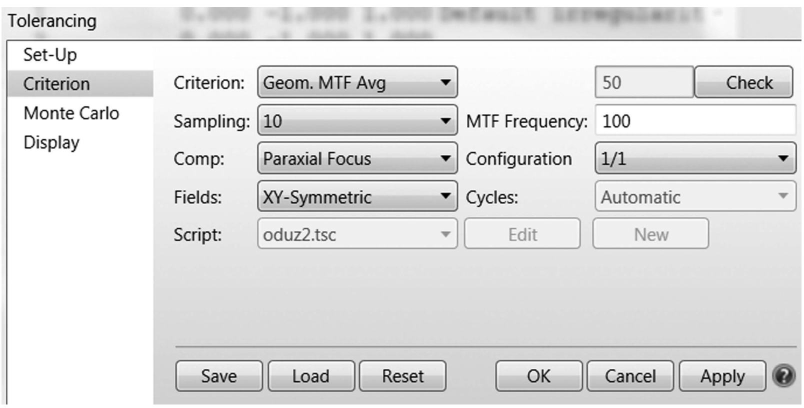


FIGURE 9.11 A *Tolerancing* box, where we can select tolerancing criterion, the times of Monte Carlo run and the display content etc.

2. Click the *Criterion* button. In the *Criterion* box to select the performance we want to check. We select *Geom. MTF Ave* since we often use MTF graphs to evaluate the lens performance. But if the lens is for some other applications, we can make different selections. Selecting any number over 10 will be adequate for *Sampling. Paraxial Focusing* is adequate for *Comp* box, *Y-Symmetric* for the *Field* box. 100 for the *MTF Frequency* box, which is about the cutoff spatial frequency of the lens.
3. Click the *Monte Carlo* button to select the number of Monte Carlo runs. Here we select 100. The other selections do not make much of a difference.
4. Click the *Display* button to select the display content of the tolerance analysis result. All the selections do not make much of a difference. We select 20 in the *Show Worst* box and uncheck all other boxes.

Then, click *OK* to run the tolerance analysis.

9.3.2 Review Tolerancing Result

9.3.2.1 Statistical Results

The tolerancing takes from a few seconds to a few minutes if we choose MTF as the performance criterion. Then, a lengthy text file named *Text Viewer* will pop up. The file contains the analysis result of every Monte Carlo run. We should not be trapped

TABLE 9.1
Summary of Tolerancing Results

Number of traceable Monte Carlo files generated: 100

Nominal	0.26993728	
Best	0.21893550	Trial 85
Worst	0.08026000	Trial 46
Mean	0.13794519	
Std Dev	0.02923369	
....		
Compensator Statistics:		
Change in back focus:		
Minimum:	–0.486866	
Maximum:	0.647973	
Mean:	0.013394	
Standard Deviation:	0.228571	
....		
90% > 0.09853432		
80% > 0.11279997		
50% > 0.13728916		
20% > 0.16047126		
10% > 0.17622409		
End of Run.		

in the details in the text file. Just go straight to the end of this text file, where the summary of the tolerance analysis results are given, as shown in Table 9.1. We separate the results into three parts by three lines. The first part gives us the statistics of the performance. The second part gives us the statistics of the compensator, usually the displacement magnitude of the image plane. The third part give us again the performance statistics in a different way.

We can see that the nominal or design MTF value is 0.26993728 (at a spatial frequency of 100 LP/mm). The mean MTF value with the current tolerance set is 0.13794519, which is only about half of the nominal MTF value, and 90% chance the assembled real lens will have an MTF value > 0.09853432, only about 37% of the nominal MTF value. The tolerancing results tell us that the tolerance ranges we set in the *Tolerance Data Editor* box significantly reduce the real lens MTF value from the nominal value.

In most commercial image lenses, the MTF value on paper at the cutoff spatial frequency should be ~0.1 above the MTF value of the real lens. By this criterion, our current tolerance ranges are too loose. We need to find the *Worst Offender*—those tolerances that contribute more than other tolerances to the drop of the MTF value, and tighten the ranges for these tolerances.

Generally speaking, we should avoid two extreme cases:

1. Design a lens with on-paper performance barely meeting the specifications, and rely on extremely tight lens element fabrication and mounting tolerance to make the real lens performance meet specifications.
2. Design a lens with on-paper performance well above the specifications, for example, MTF value at the cutoff frequency is twice higher than the specified MTF value, use poorly fabricated and mounted element, and hope the real lens can still perform OK.

9.3.2.2 Worst Offender

Somewhere around the middle of the *Text Viewer* file, we can find the *Worst Offender.* Shown in Table 9.2 are the first 20 worst offenders. We can select in the *Tolerancing* box to display more or less worst offenders.

The first column in Table 9.2 is the tolerance type, the second column is the tolerance range, the third column is the current value of the criterion (in this case, it's the MTF average value), and the fourth column is the value of criterion change. Then, we can interpret the content in Table 9.2. The first row means thickness of surface 3 with surface 5 as *Adjust* and tolerance 0.1 will cause the MTF value to change by –0.12176580 from the nominal (0.26993728) to 0.14817149. The third row means the element formed by surfaces 3 and 5 (the doublet) with a mounting tolerance of 0.2° in the x direction will cause the MTF value to change by –0.13633925 from the nominal value. All other rows in Table 9.2 can be understood in a similar way, and so we will not explain every row. For this double Gauss lens, the tolerancing results listed in Table 9.2 show that the first doublet (involves every tolerance between surfaces 3 and 5) is the most sensitive one.

9.3.2.3 Tighten Tolerance Ranges

To improve the performance of the real lens, we need to go to *Tolerance Data Editor* box, and tighten the ranges of some tolerances listed as the worst offender. It does not

TABLE 9.2
Worst Offender List

Worst Offenders:

Type			Value	Criterion	Change
TTHI	3	5	−0.10000000	0.14817149	−0.12176580
TTHI	4	5	−0.10000000	0.14928570	−0.12065158
TETX	3	5	−0.20000000	0.15238050	−0.11755678
TETX	3	5	0.20000000	0.15238050	−0.11755678
TETY	3	5	−0.20000000	0.15238050	−0.11755678
TETY	3	5	0.20000000	0.15238050	−0.11755678
TETX	1	2	−0.20000000	0.15313362	−0.11680366
TETX	1	2	0.20000000	0.15313362	−0.11680366
TETY	1	2	−0.20000000	0.15313362	−0.11680366
TETY	1	2	0.20000000	0.15313362	−0.11680366
TTHI	4	5	0.10000000	0.18691743	−0.08301985
TTHI	3	5	0.10000000	0.18802342	−0.08191386
TABB	4		0.33848240	0.19287258	−0.07706470
TEDX	3	5	−0.05000000	0.21522512	−0.05471216
TEDX	3	5	0.05000000	0.21522512	−0.05471216
TEDY	3	5	−0.05000000	0.21522512	−0.05471216
TEDY	3	5	0.05000000	0.21522512	−0.05471216
TETX	10	11	−0.20000000	0.21792521	−0.05201207
TETX	10	11	0.20000000	0.21792521	−0.05201207
TETY	10	11	−0.20000000	0.21792521	−0.05201207

make sense to tighten some tolerances to an extreme, while leave some other tolerances very loose. We want to evenly tighten the tolerances. Carefully looking at the details of Table 9.2, we can find that:

1. The first 10 tolerances in Table 9.2 cause changes about twice larger than the last seven tolerances. So, if we want to cut the ranges of the last seven tolerances by half, we should cut the ranges of the first 10 tolerances to about one-fourth, in order to maintain even tolerancing.
2. With point 1 being said, we also need to check whether the tightened tolerance ranges are achievable.

Shown in Figure 9.12 is the lens manufacturing tolerance chart from Optimax Systems Inc. that provides a general guidance on the tolerance ranges. Different lens vendors have similar guidance. There are usually three tolerance grades: commercial, precision, and high precision. We should try to avoid tightening tolerances beyond the high-precision tolerances, particularly avoid using glass "melt data" as explained in Section 9.1.6. If one tolerance is already very tight, it still reduces the lens performance significantly. We may have to accept this tolerance range and try to improve the lens performance by tightening the other tolerances, or we have to

ATTRIBUTE	COMMERCIAL	PRECISION	HIGH PRECISION
Glass Material(n_d,v_d)	±0.001,± 0.8%	±0.0005, ±0.5%	Melt Data
Diameter (mm)	±0.00/-0.10	+0.000/-0.025	+0.000/-0.015
Center Thickness (mm)	±0.150	±0.050	±0.025
SAG (mm)	±0.050	±0.025	±0.015
Clear Aperture	80%	90%	90%
Radius (larger of two)	±0.2% or 5fr	±0.1% or 3fr	±0.05% or 1fr
Irregularity - Interferometer (fringes)	2	0.5	0.2
Irregularity - Profilometer (microns)	±10	±1	±0.5
Wedge Lens (ETD, mm)	0.050	0.010	0.005
Wedge Prism (TIA, arc min)	±5	±1	±0.5
Bevels (face width @ 45°, mm)	< 1.0	< 0.5	< 0.5
Scratch - DIG (MIL-PRF-13830B)	80 - 50	60 - 40	20 - 10
Surface Roughness (Å rms)	50	20	10
AR Coating(R_{Ave})	MgF_2 R<1.5%	BBAR R<0.5%	V-coat R<0.2%

FIGURE 9.12 A typical lens manufacturing tolerance chart. There are three grades of tolerance. Moving up one grade costs about 50% more. Adapted from Optimax Manufacturing Tolerance Chart, Copyright © 2016 by Optimax Systems, Inc. Reprinted by permission of Optimax Systems, Inc.

redesign the lens, usually use more elements with milder surface profiles and smaller incident/exit ray angles. Redesign is not an exciting thing. It's better to pay attention to element shapes and incident/exit ray angles during the first design.

After we tighten the ranges of some tolerances in the worst offender list, we need to run tolerancing again to check the performance. We may find several new worst offenders that cause big changes in the criterion because tolerancing results are statistical. We need to tighten the ranges of these new worst offenders and run tolerancing again. This process will go on for a few cycles till the tolerancing results consistently meet the specifications. We can once run Monte Carlo analysis several thousand times and display a few hundred worst offenders to tighten. One big cycle equals several small cycles.

After a few rounds of tightening, we obtain the final tolerance set shown in Table 9.3 with 90% probability MTF average value > 0.17 (~0.1 drop from the nominal value of ~0.27).

TABLE 9.3
Tolerance Summary

SURFACE CENTERED TOLERANCES:

Surf	Radius	Tol Min	Tol Max	Power	Irreg	Thickness	Tol Min	Tol Max
1	40.629	–	–	5	1	6.8168	–0.1	0.1
2	97.095	–	–	5	1	0.7715	–0.05	0.05
3	24.855	–	–	5	1	8.6314	–0.025	0.025
4	57.524	–	–	5	1	2.0034	–0.025	0.025
5	16.808	–	–	5	1	11.132	–0.1	0.1
6	Infinity	–	–	–	–	13.253	–0.05	0.05
7	–20.288	–	–	5	1	1.9999	–0.05	0.05
8	622.58	–	–	5	1	8.7629	–0.1	0.1
9	–27.74	–	–	5	1	0.49945	–0.1	0.1
10	163.36	–	–	5	1	6.7399	–0.1	0.1
11	–93.082	–	–	5	1	40	–	–
12	Infinity	–	–	–	–	0	–	–

SURFACE DECENTER/TILT TOLERANCES:

Surf	Decenter X	Decenter Y	Tilt X	Tilt Y	TIR X	TIR Y
1	–	–	–	–	0.02	0.02
2	–	–	–	–	0.02	0.02
3	–	–	–	–	0.02	0.02
4	–	–	–	–	0.02	0.02
5	–	–	–	–	0.015	0.015
6	–	–	–	–	–	–
7	–	–	–	–	0.02	0.02
8	–	–	–	–	0.02	0.02
9	–	–	–	–	0.02	0.02
10	–	–	–	–	0.02	0.02
11	–	–	–	–	0.02	0.02
12	–	–	–	–	–	–

GLASS TOLERANCES:

Surf	Glass	Index Tol	Abbe Tol
1	N-LAK34	0.001	0.27
3	N-PSK53A	0.001	0.32
4	SF2	0.001	0.17
7	F2	0.001	0.18
8	N-LAK34	0.001	0.27
10	N-LAK34	0.001	0.54499

ELEMENT TOLERANCES:

Ele#	Srf1	Srf2	Decenter X	Decenter Y	Tilt X	Tilt Y
1	1	2	0.05	0.05	0.05	0.05
2	3	5	0.03	0.03	0.05	0.05
3	7	9	0.03	0.03	0.1	0.1
4	10	11	0.05	0.05	0.1	0.1

9.3.3 Tolerance Summary

After we finish tolerancing, we can display the result in a well-organized format. Clicking *Tolerance/Tolerance Summary*, we can open a *Tolerance Summary* text file as shown in Table 9.3. The content is pretty clear and doesn't need more explanations. Most tolerances listed in Table 9.3 are in the commercial and precision grades. Note that the Abbe numbers of five glasses have been tightened from 1% to 0.5%.

9.3.4 Tolerance Versus Cost

Lens elements with tight fabrication tolerances cost more. Lens manufacturers have similar tolerance versus cost guidelines. Generally speaking, moving up one grade costs about 50% more. The real situation is often more complex. Some tolerances of one element may fall in the range of one grade, and some other tolerances may fall in the ranges of another grade. Lens manufacturers will quote a price based on overal tolerances.