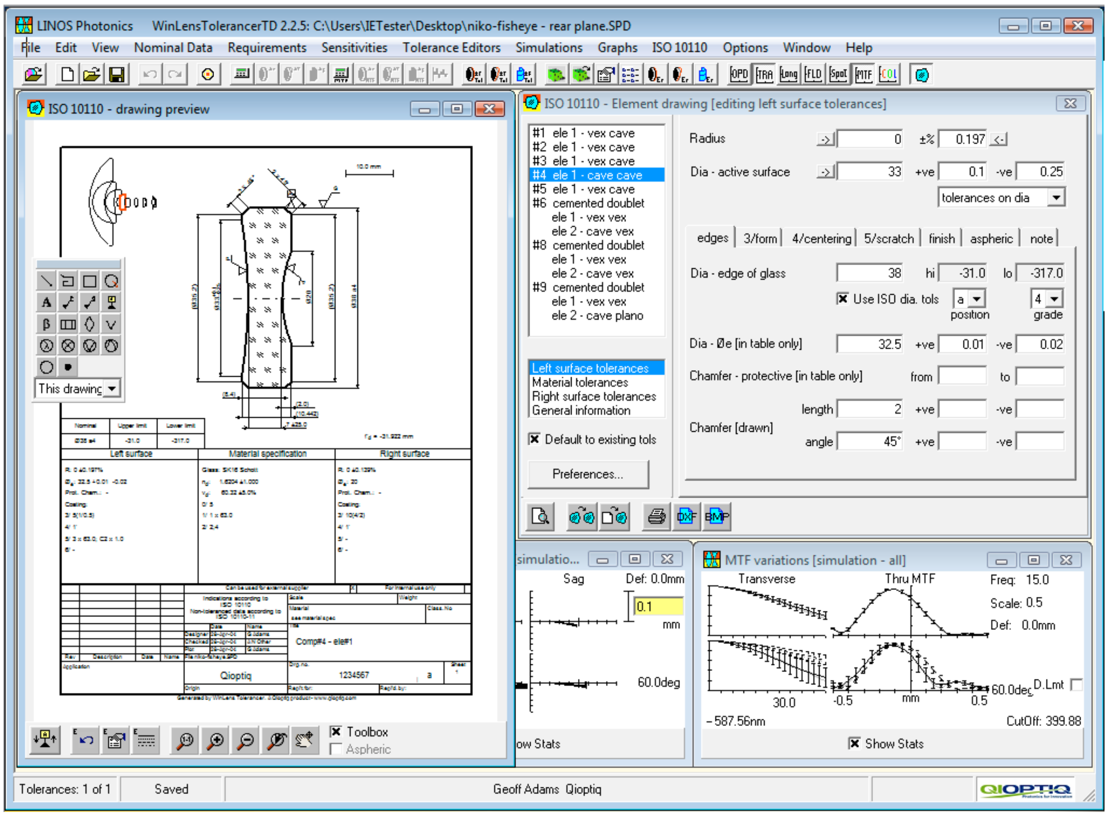
WinLens Tolerancer

Optical Design Software

users guide: tolerancing & engineering drawings



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Summary

WinLens Tolerancer is designed to help optical designers select a reasonable set of tolerances for an optical system. The program has sensitivity analyses, tolerance editors and Monte Carlo simulations. Users can now model the effects of specific sets of errors. It can also generate engineering drawings according to ISO 10110.

It is designed for systems with nominal rotational symmetry.

In this manual we discuss tolerancing, and show how to use WinLens Tolerancer via a worked example and detailed notes.

New features:

v2.2.2

- User defined errors [chapter 9]

v2.2.1

- ISO 10110 element & component drawings [chapter 8]

v2.1.3 [may 2003].

- extra help in selecting performance specifications [section 3.1]
- compensator added [user selectable air space] [chapter 7]
- choice of units for angular errors [rad, min, mrad]
- improvements to simulation list

v2.1.1

- Bar graph display of sensitivities
- New glass data files – as controlled by Material Editor utility

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The manual

Revision 2.2.3

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Contents

1. Introduction

"Tol.er.ance. n -s[ME tolleraunce, fr MF tolerance, fr L tolerantia, fr tolerant-, tolerans (pres part of tolere: to endure, put up with) c y]…
…3:b the range of variation permitted in maintaining a specified dimension in machining a piece: the difference between the upper and lower limits between which a size must be held. compare **allowance**."

Webster's third New International Dictionary

The life cycle of any product may be split into several distinct stages: conception, development, production and sale. Once the potential of the initial idea has been verified, all constructional parameters must be selected and then optimised to improve performance, reduce costs etc. When development is complete, engineering drawings will be prepared using the appropriate standards[1]. These will be the blue prints for the production process.

Since no process is perfect, small dimensional deviations will occur from the nominal design. These may prevent the system being assembled, or, more usually, degrade the performance of the system.

Therefore as part of the design process, maximum acceptable variations in the parameters have to be specified. This activity is known as tolerancing.

Tolerancing is constrained by two conflicting requirements:

- To maintain performance [implies tight tolerances]
- To minimise cost [implies loose tolerances]

Optical designs are no exception to the general rule, and must therefore be toleranced. However, optical designers will often see tolerancing as a task for the mechanical engineer or even the estimating department. Such a view is positively harmful; only the optical designer has the knowledge to assess the impact of tolerances on the system performance.

Unfortunately, this is not a trivial task. There are:

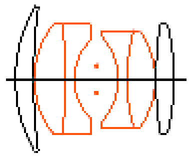
- many different types of parameter requiring tolerancing
- many optical effects of those parameters to be considered
- statistical effects

WinLens Tolerancer has been written to provide the optical designer with the necessary tools for this task.

[1] As from *v2.2.1* WinLens Tol can generate element and component drawings to ISO 10110 [see chapter 8]

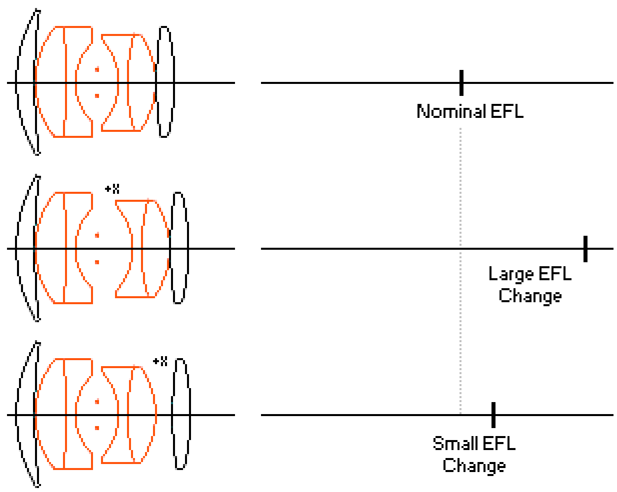
1.1 Tolerancing and optical systems

The end result of the design process is an optimised optical system.



This system is defined by a particular set of design parameters, while its optical performance will be described by many quantities such as focal length [EFL], spot size and MTF. These must satisfy the design specifications.

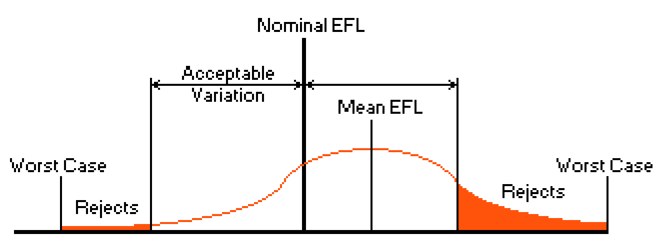
In this section we will consider the EFL [however the principles apply to all performance descriptors]. If a small change is made to a design parameter, then the EFL will alter.



Some parameters are more sensitive than others, i.e. have more impact on the EFL, if they are changed.

During manufacture of a lens, small random errors will occur in the value of each parameter, e.g. radius 1 may be 70.15mm instead of 70.10mm, radius 2 may be 205.23mm instead of 205.17mm etc. The EFL for this lens is a function of all the design errors.

If a batch of lenses is produced, the errors will differ from system to system, and so the EFL will also vary from system to system. Some systems will have an acceptable EFL, whilst others will be outside the permissible limits.



Spread in EFL for a batch of lenses

The larger the errors, the larger the spread of EFL, and the more systems will fail. The maximum error is specified by the tolerance assigned by the designer to each design parameter.

The aim of tolerancing is to select tolerances so that most[2] systems will satisfy the design criterion.

Obviously this could be achieved by assigning really tight tolerances on all parameters. However, tight tolerances are more costly to attain. Therefore the designer has to assign the loosest possible tolerances consistent with a low failure rate.

In order to do this effectively, the designer will need to identify which parameters are sensitive, and therefore need tighter tolerances. Furthermore he will want to have rapid feedback on the impact of a particular tolerance upon the expected distribution[s] of the performance descriptors.

It is possible to predict the latter from a knowledge of:

- tolerances and typical error distributions
- sensitivities [e.g. changes in aberration]

Statistical methods are used to obtain these predictions, which can then be verified by Monte Carlo simulations of the manufacture of a batch of systems.

When tolerancing is complete, engineering drawings of the elements and the cemented components have to be prepared for the glass shops.

Finally, during production it may be necessary to re-measure and re-analyse particular systems [at least for higher cost systems]

[2] Worst case tolerancing is not generally cost effective. As shown in the diagram on the previous case, the worst case [when the effects of the errors all add together] will almost never occur.

1.2 Manual Structure

The chapters of this manual are divided into three sections. These are as follows:

Ch 2	Program installation/basic structure/simple example
Ch 3 - 9	Detailed program use
Ch 10 - 12	Tolerancing notes/Hints & Tips

We suggest that you follow the simple example in section 2.4 in order get a quick overview of WinLens Tolerancer.

There are no magic methods which will automatically generate the ultimate set of tolerances for your systems. Instead WinLens Tolerancer offers a set of tools to help you in this task, including multi-level undo-redo facilities.

You will need to know which parameters are most sensitive. You will want to be able to get quick feedback on the impact of a given tolerance change. You will want to simulate the production of a batch of systems. All this is possible with WinLens Tolerancer.

You may now select an air-space between components to act as a compensator [Ch 7]

You may now [*v2.2.1*] also generate element and cemented component drawings to ISO 10110 [Ch 8] in a very flexible editor & preview form.

You can also now [*v2.2.2*] enter specific error[s] and the see the impact the various graphs. [Ch 9]

You are not forced to use any of these tools in any particular order. Please follow the example in section 2.4 and then explore the manual and program.

2. Program Overview

This chapter provides an introduction to WinLens Tolerancer, and a simple example of a tolerancing session.

2.1 Program Installation/Requirements

- WinLens Tolerancer runs under Windows XP, Vista & Windows 7. It will run on any PC which can comfortably run those systems.
- It may run on earlier versions of Windows.
-

2.2 Assumptions and Limitations

We assume that you are familiar with WinLens, and the various analysis tools, such as TRA, OPD, Field Aberrations, MTF and Spot Diagrams [these are fully described in the WinLens help system].

WinLens Tolerancer will only work for systems with nominal rotation symmetry.

WinLens Tolerancer does not model the effects of:

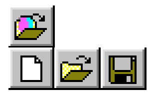
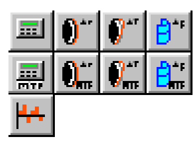
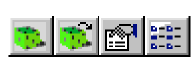
- material imperfections[3]
- surface imperfection, texture or treatment

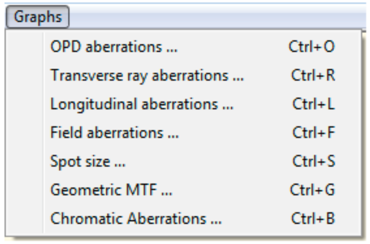
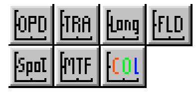
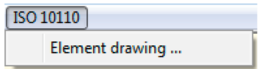
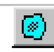
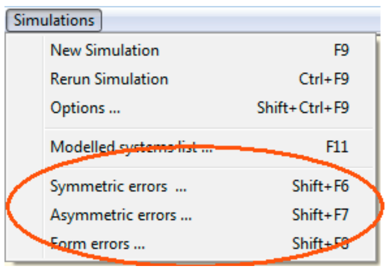
Pickups are ignored.

[3] birefringence, bubbles and inclusions or inhomogeniety and striae. However in the ISO 10110 drawings [Ch 8], you may specify these items.

2.3 Program Outline

WinLens Tolerancer offers a number of editors and analysis tools. These may be accessed from the menu and from the toolbar.

Function	Menu	Toolbar	Notes	Ch
File Operations	File Open Lens File ... New Tolerances Ctrl+N Open Tolerances ... Save Tolerances Save Tolerances As ... Exit Ctrl+Q		• Load lens file • New tolerance set • Load/Save tolerance file	
Nominal System Data	Nominal Data System Data ... System Parameters ... Surface Data ... Lens Drawing ... Zoom Manager...		Shows data for nominal system [as check to make sure have loaded correct system] Zoom manager selects current zoom for editing	
Requirements [specifications]	Requirements		Specify allowable change in optical performance [aberrations]	Ch 3
Sensitivities	Sensitivities Calc aberration sensitivities F2 Symmetric [aberrations] ... F3 Asymmetric [aberrations] ... F4 Form [aberrations] ... F5 Calc spot/mtf sensitivities Ctrl+F2 Symmetric [spot/mtf] ... Ctrl+F3 Asymmetric [spot/mtf] ... Ctrl+F4 Form [spot/mtf] ... Ctrl+F5 BarGraphs... Shift+F2		Calculate and display sensitivities for single aberrations. Calculate and display sensitivities for MTF and spot size [non linear functions of the parameters] Bargraph plots for individual aberrations	Ch 4
Tolerance Editors	Tolerance Editors Symmetric ... F6 Asymmetric ... F7 Form ... F8		Edit tolerance for symmetric/ asymmetric and form errors. Get statistical predictions of impact of those tolerances.	Ch 5
Simulations	Simulations New Simulation F9 Rerun Simulation Ctrl+F9 Options ... Shift+Ctrl+F9 Modelled systems list ... F11 Symmetric errors ... Shift+F6 Asymmetric errors ... Shift+F7 Form errors ... Shift+F8		Monte Carlo simulations: Run simulations List of system in simulations [with aberrations for those systems] Displays of errors in selected system in simulations	Ch 6

Graphs			OPD's, TRA's, longitudinal abns, Field abns, Spot diagrams, MTF and chromatic aberrations. For: • nominal system • sensitivity • Monte Carlo simulations	
ISO Drawings [new v2.2.1]			Element & cemented component drawings to ISO 10110	Ch 8
User errors [new v2.2.2]			Specify & analyse effects of a set of user defined errors	Ch 9

2.4 Tolerancing example

This section briefly runs through a typical tolerancing session. It covers:

- Loading a lens for tolerancing
- Running sensitivity analysis
- Setting performance requirements
- Editing tolerances
- Running simulations
- Saving tolerances

WinLens Tolerancer is designed so that you can iterate easily between editing tolerances and running simulations to check those tolerances.

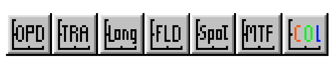
2.4.1 Loading a lens for tolerancing

Click this icon in the toolbar. WinLens Tolerancer will show the standard windows file dialog. Select and load the file WLDG001.SPD [this will be installed in same folder as WinLens Tolerancer.

You will now see a dialog with various options for locating the image plane during sensitivity analysis and Monte Carlo simulations. Select the second option [Simple Refocus] on the dialog. If you need to, you can alter your choice later on by selecting the 'Options' item in the main menu.

To make sure this is the correct system, you can look at the lens drawing and other tables describing the nominal system. Pull down the 'Nominal Data' menu item, and select the items you wish to review. These are the same as in WinLens, and so will not be described further.

You can also look at the system performance with various graphs. These graphs not only show the nominal aberrations, but can be



used to illustrate sensitivities and to display the results of Monte Carlo simulations. You can look at all or any of these. However for this example, load the TRA [transverse ray aberration plot], Field aberration plot and the MTF plot.

2.4.2 Running sensitivity analysis

There are two sensitivity analyses available [see chapter 4]:

- single aberrations [linear functions of errors]
- spot/mtf [non linear functions of errors]

The former is almost always quicker, so we will run this. Simply click

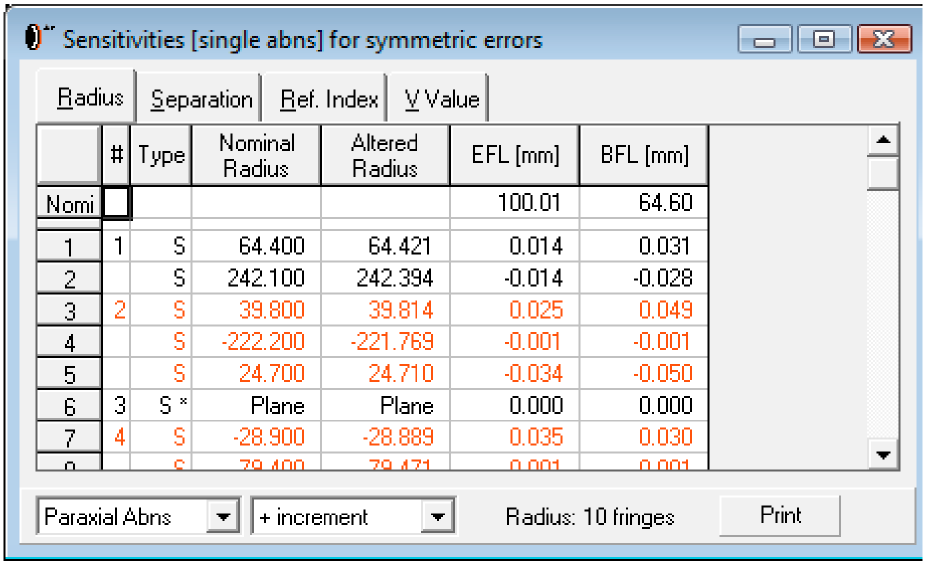
the button and wait while the analysis is being performed.

While the analysis is being performed you will see that the TRA and Field aberration plots are being continually updated, to show the changes due to each parameter change.

However, the MTF plot is not updated, as the MTF is not calculated during the single aberration sensitivity analysis. If we had performed the Spot/MTF analysis, then the MTF plots would have been updated.

When the analysis is complete, you will see that the sensitivity display buttons are now enabled. Let us look at the results for the symmetric errors [curvature, separation, index & V Value]. Click on the button, and you will see a new form, as shown below:

Select parameter type:
- Radius
- Separation
- Refractive Index
- VValue

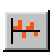


	#	Type	Nominal Radius	Altered Radius	EFL [mm]	BFL [mm]
Nomi					100.01	64.60
1	1	S	64.400	64.421	0.014	0.031
2		S	242.100	242.394	-0.014	-0.028
3	2	S	39.800	39.814	0.025	0.049
4		S	-222.200	-221.769	-0.001	-0.001
5		S	24.700	24.710	-0.034	-0.050
6	3	S *	Plane	Plane	0.000	0.000
7	4	S	-28.900	-28.889	0.035	0.030

Select sensitivities for:
- Paraxial Aberrations
- Seidel Aberrations
- Real Chief Ray

Each row corresponds to one parameter. So, if you look at row 2, you will see the impact of changing curvature 2 by 5 fringes. Initially paraxial effects are shown, so we see that the EFL changes by -0.007mm and the BFL changes by -0.014mm.

Sensitivities can now [*v2.1*] be also shown in a bar graph format:



note that these are relative values

Initially we see the results of changing the radius parameters. To see the results for other parameter types, simply click on the appropriate tab at the top of the form.

By selecting from the drop down list at bottom left, you can also see the changes in the Seidel aberrations or the changes in the real ray aberrations [Astigmatism, Distortion and Lateral Colour] for the extreme chief ray.

If you click on any of the rows, note how the TRA plot is automatically updated. The nominal aberrations are plotted in light grey, whilst the aberrations for the perturbed system are shown in black.

The MTF plot is not updated, because the Spot/MTF sensitivities have not yet been found.

You may wish to look at the equivalent displays for Asymmetric errors and for Form errors. These are described in Chapter 4.

You may also wish to run the Spot/MTF sensitivity analysis at this point.

2.4.3 Setting performance requirements

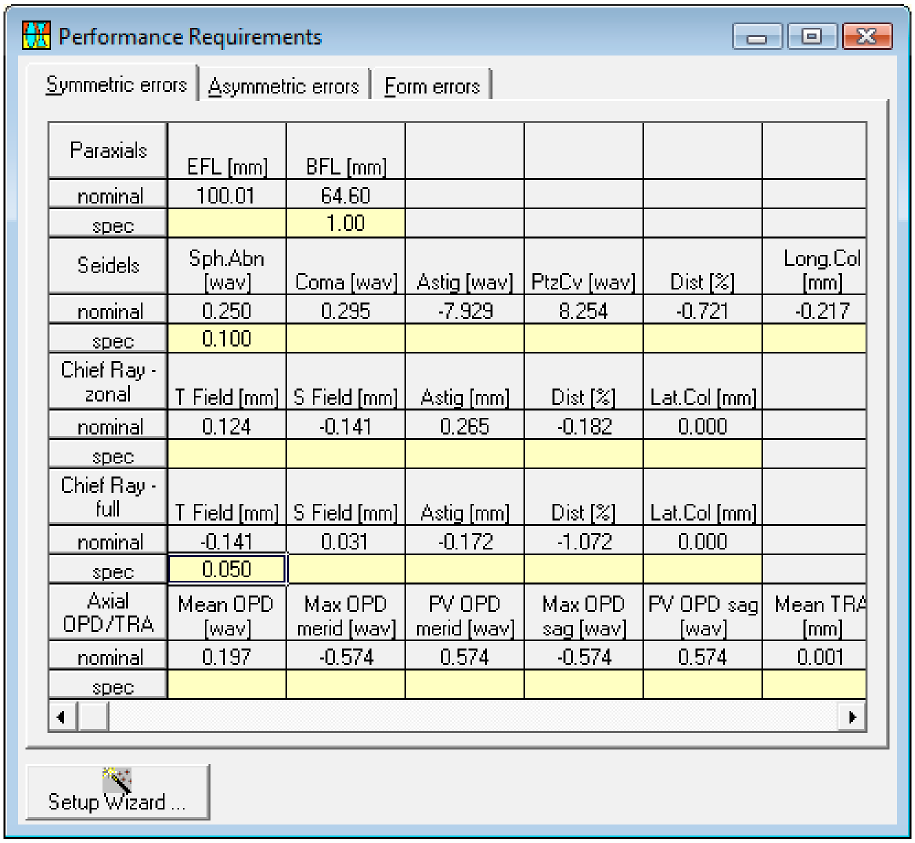
Tolerancing could be undertaken by simply selecting/editing a set of tolerances and running an MTF simulation. However iterating that loop until you are satisfied could take quite a long time and would be very frustrating.

There is a better approach available in WinLens Tolerancer:

- Select some target aberrations, and enter allowable variations [requirements] for those aberrations.
- In the editors, you will then see predictions of the ranges of these aberrations for a batch of systems.
- On changing the tolerances these predictions update very quickly, providing rapid feedback.
- When the predictions seem ok, then run simulations to validate the predictions.

> In chapter 3 we give some notes on how to choose these specifications.

To enter your requirements, click on the button. You will then see the requirements form. For this example, we are just going to enter requirements for aberrations changing because of symmetric errors. When the form is loaded, enter in the values for BFL, SphAbn and T Field Astigmatism [as shown in the yellow [editable] cells].



Paraxials	EFL [mm]	BFL [mm]				
nominal	100.01	64.60				
spec		1.00				
Seidels	Sph.Abn [wav]	Coma [wav]	Astig [wav]	PtzCv [wav]	Dist [%]	Long.Col [mm]
nominal	0.250	0.295	-7.929	8.254	-0.721	-0.217
spec	0.100					
Chief Ray - zonal	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]	
nominal	0.124	-0.141	0.265	-0.182	0.000	
spec						
Chief Ray - full	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]	
nominal	-0.141	0.031	-0.172	-1.072	0.000	
spec	0.050					
Axial OPD/TRA	Mean OPD [wav]	Max OPD merid [wav]	PV OPD merid [wav]	Max OPD sag [wav]	PV OPD sag [wav]	Mean TRA [mm]
nominal	0.197	-0.574	0.574	-0.574	0.574	0.001
spec						

This means that we want the variation in:

- BFL to be less than ±1mm about the nominal 64.5mm
- Spherical Aberration[Seidel] to be less than ±0.1waves
- T Field Astigmatism to be less than ±0.50mm

Having entered these requirements, and obtained the sensitivities we are now ready to edit tolerances.

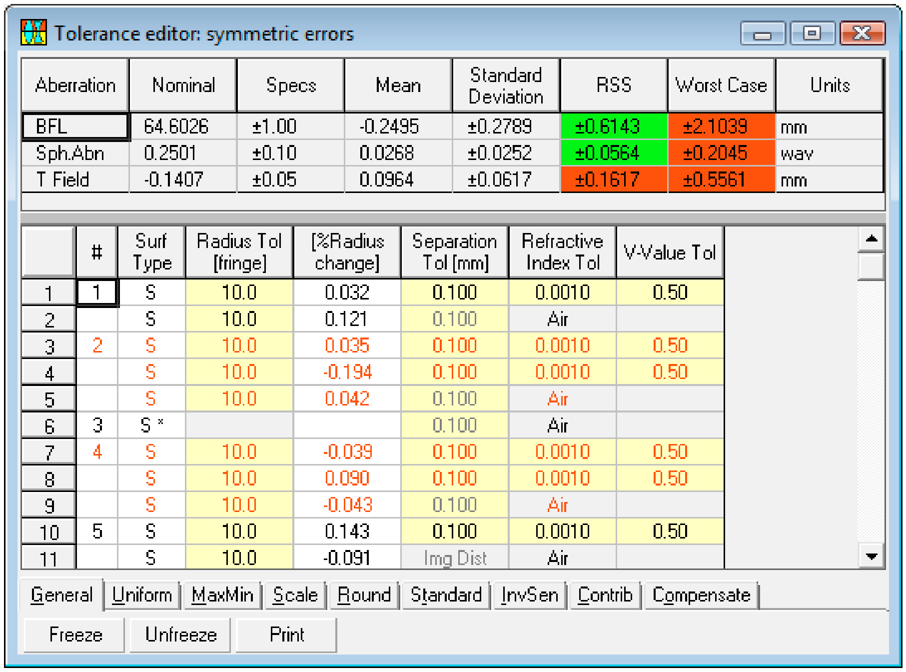
2.4.4 Editing tolerances

Again we will just edit symmetric tolerances, since the operations of all the editors are very similar. Click on the button in the toolbar, and you will see the following:

Requirement feedback area: Shows statistics of distributions of the selected aberrations

Tolerance display area: for direct editing 'frozen' tolerances in blue

Tools area: for editing many tolerances and showing contributions



When you first load a system, WinLens Tolerancer assigns a default set of tolerances [±10 fringes on radius, separation of ±0.1mm etc]. These are shown in the central table.

Above this, at top of the form, you can see the selected aberrations and the predicted statistics [mean, standard deviation, RSS and worst case] for a batch.

As a handy guide, aim to make the RSS[4] value less than the specification. If the RSS value is back-lit in red [as here the T Field Astigmatism], you need to tighten up tolerances.

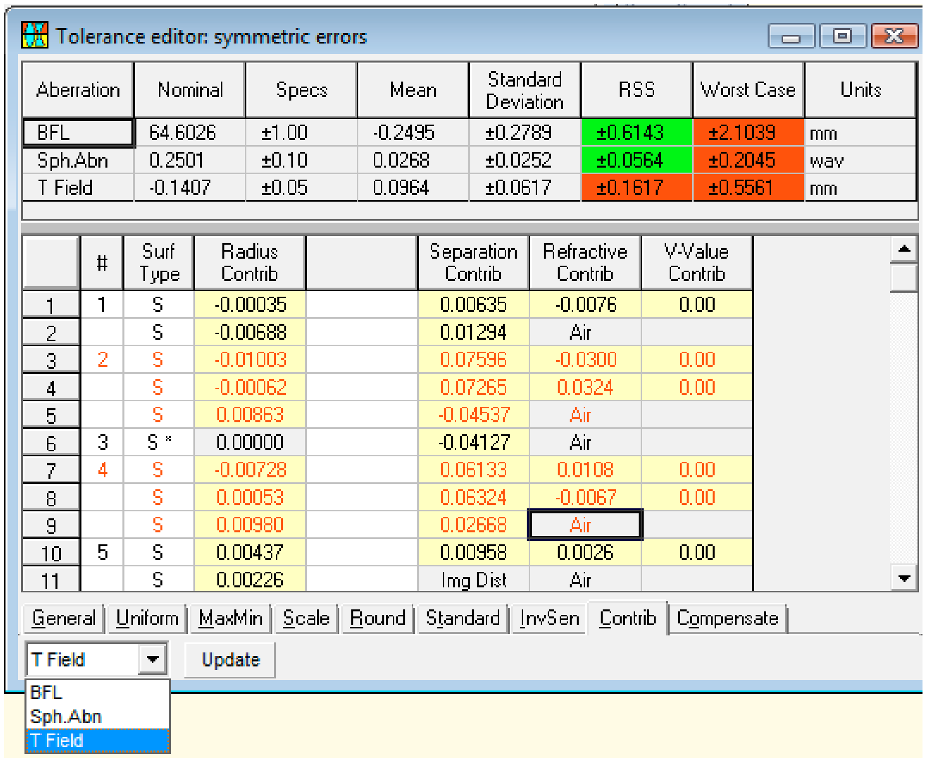
By contrast, the worst case will usually exceed the specification, but this can be ignored.

The main question is: "what tolerances are the most effective tolerances to tighten?".

WinLens Tolerancer will allow you to see the contributions from each parameter [at its current tolerance limit] to any of the specified aberrations. Simply click on the 'Contrib' tab in the tools section at the bottom of the form.

Then drop down the aberration dialog [bottom left] and select the T Field astigmatism. Click on the update button. The tolerances will be replaced by the contributions.

[4] The RSS value is the standard deviation of the aberration distribution, when all errors are at their tolerance limit.
Normally errors will be less than the tolerance, so the RSS will be larger than the predicted standard deviation.



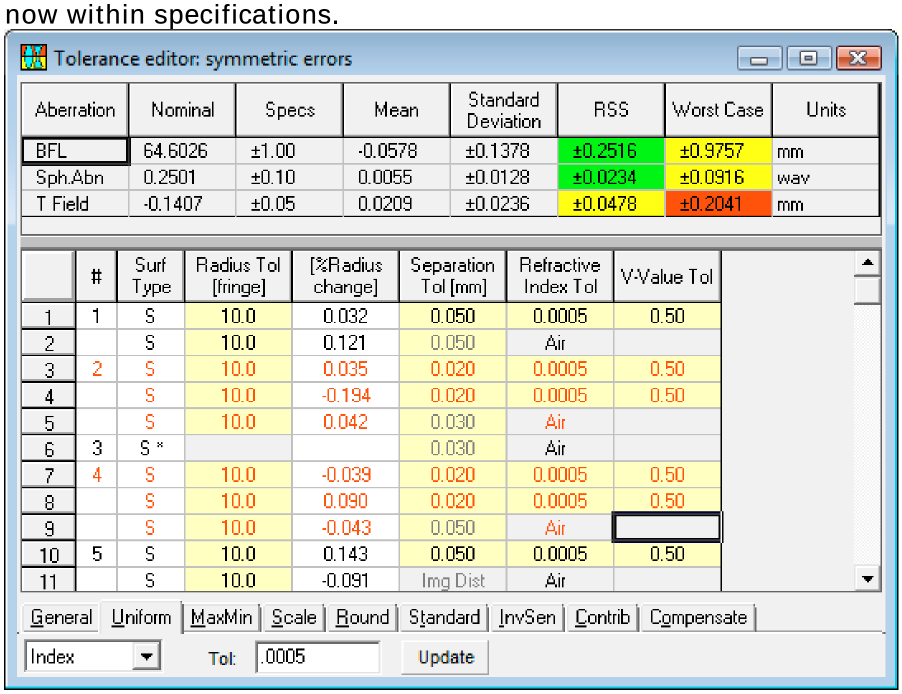
Aberration	Nominal	Specs	Mean	Standard Deviation	RSS	Worst Case	Units
BFL	64.6026	±1.00	-0.2495	±0.2789	±0.6143	±2.1039	mm
Sph.Abn	0.2501	±0.10	0.0268	±0.0252	±0.0564	±0.2045	wav
T Field	-0.1407	±0.05	0.0964	±0.0617	±0.1617	±0.5561	mm

	#	Surf Type	Radius Contrib		Separation Contrib	Refractive Contrib	V-Value Contrib
1	1	S	-0.00035		0.00635	-0.0076	0.00
2		S	-0.00688		0.01294	Air	
3	2	S	-0.01003		0.07596	-0.0300	0.00
4		S	-0.00062		0.07265	0.0324	0.00
5		S	0.00863		-0.04537	Air	
6	3	S *	0.00000		-0.04127	Air	
7	4	S	-0.00728		0.06133	0.0108	0.00
8		S	0.00053		0.06324	-0.0067	0.00
9		S	0.00980		0.02668	Air	
10	5	S	0.00437		0.00958	0.0026	0.00
11		S	0.00226		Img Dist	Air	

Upon inspection it is quite clear that the separations for the central doublets, and air spaces are most significant and therefore have to be tightened.

These tolerances are quite tight. As an alternative, you may use a compensator [v2.1.3]. This is discussed in chapter 7.

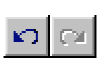
Simply click on the spreadsheet, and the tolerances will reappear. Type in the separation tolerances of .02 for glass spaces and .03 for air spaces. Also, reduce the refractive index tolerances from 0.001 to 0.0005. Note how the predicted range of astigmatism falls, and is now within specifications.



Aberration	Nominal	Specs	Mean	Standard Deviation	RSS	Worst Case	Units
BFL	64.6026	±1.00	-0.0578	±0.1378	±0.2516	±0.9757	mm
Sph.Abn	0.2501	±0.10	0.0055	±0.0128	±0.0234	±0.0916	wav
T Field	-0.1407	±0.05	0.0209	±0.0236	±0.0478	±0.2041	mm

	#	Surf Type	Radius Tol [fringe]	[%Radius change]	Separation Tol [mm]	Refractive Index Tol	V-Value Tol
1	1	S	10.0	0.032	0.050	0.0005	0.50
2		S	10.0	0.121	0.050	Air	
3	2	S	10.0	0.035	0.020	0.0005	0.50
4		S	10.0	-0.194	0.020	0.0005	0.50
5		S	10.0	0.042	0.030	Air	
6	3	S *			0.030	Air	
7	4	S	10.0	-0.039	0.020	0.0005	0.50
8		S	10.0	0.090	0.020	0.0005	0.50
9		S	10.0	-0.043	0.050	Air	
10	5	S	10.0	0.143	0.050	0.0005	0.50
11		S	10.0	-0.091	Img Dist	Air	

Try using the multi-level undo-redo facilities. These are accessed through icons on the main toolbar.

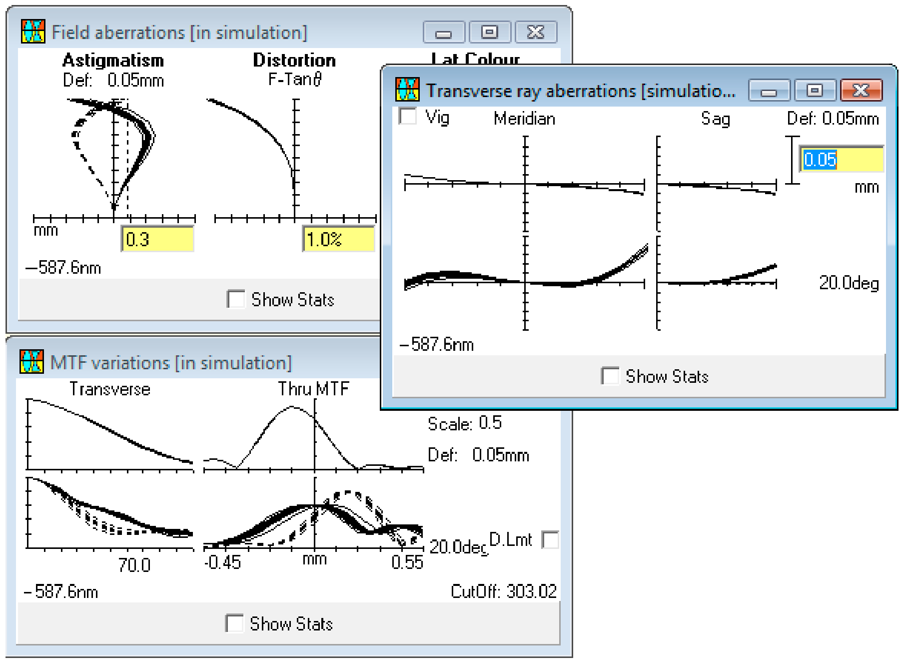


Since this set of tolerances look ok, it is time to run a simulation.

2.4.5 Running simulations

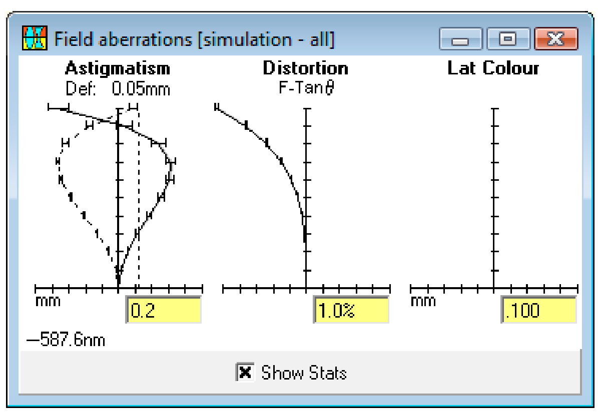
A Monte Carlo simulation models the manufacture of a batch of lenses. Errors[5] are randomly added to the design parameters, and the resultant system is analysed. This is repeated for as many systems are in the batch.

To start the simulation, click the button on the toolbar. As the simulation proceeds, note how the aberration plots for each new lens are overlaid on the existing curves.



When the simulation is finished, you can:

1. load other graphs and see the simulations results.
2. toggle between raw plots [as shown above] and statistical summaries [shown below] by clicking on the 'Show stats' check box at bottom of each plot.



There are further ways to exploit this simulation. You will need

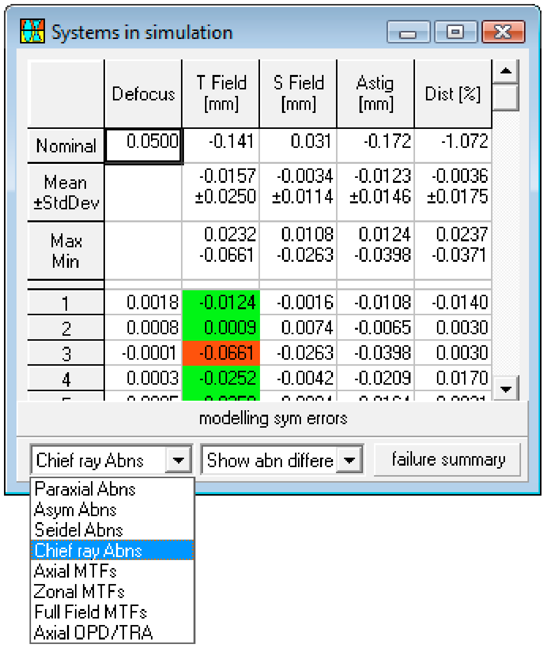
to load the modelled system list. Click this button, and you will see a new spreadsheet appear. Each system is represented by

[5] The maximum error for any parameter is defined by the tolerance on that parameter. The distributions of the errors are appropriate to the type of parameter.

one row. Each row contains information about one set of aberrations [e.g. paraxial or seidels or ... etc, as specified by drop down list at bottom left of the form]

You can now sort the spread-sheet [v2.1.3] by clicking on a column header. In this way, it is easy to see which systems have generated the largest change in a specific aberration

If one the displayed aberrations was specified [displayed in the top of a tolerance editor] then that column will be colour coded
- green if within spec
- red if outside spec

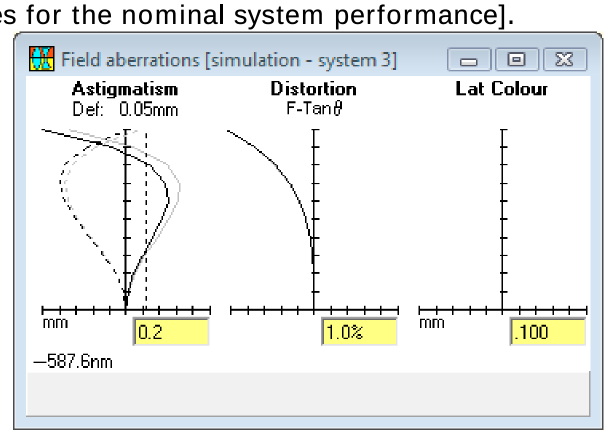


Thus you can see the changes in the aberrations.

The top row shows the nominal system values, and the next row shows the statistics for these aberrations, averaged over the batch.

Click a row, and the aberration plots will show the curves for that system [plus faint lines for the nominal system performance].

If you click on the top row, you will only see the nominal curves, whilst clicking on the second row regenerates the curves for the entire simulation.



Finally, you can view the errors for any system in the list. Pull down the simulations and select the 'symmetric errors...' option.

2.4.6 Saving tolerances

To save the current set of tolerances, simply click the button in the toolbar. You will then see a standard file save dialog.

3. Requirements [Specifications]

In section 3.1 below we will discuss in more detail how to select specifications

Performance requirements are maximum acceptable changes in the aberrations as a result of manufacturing errors.

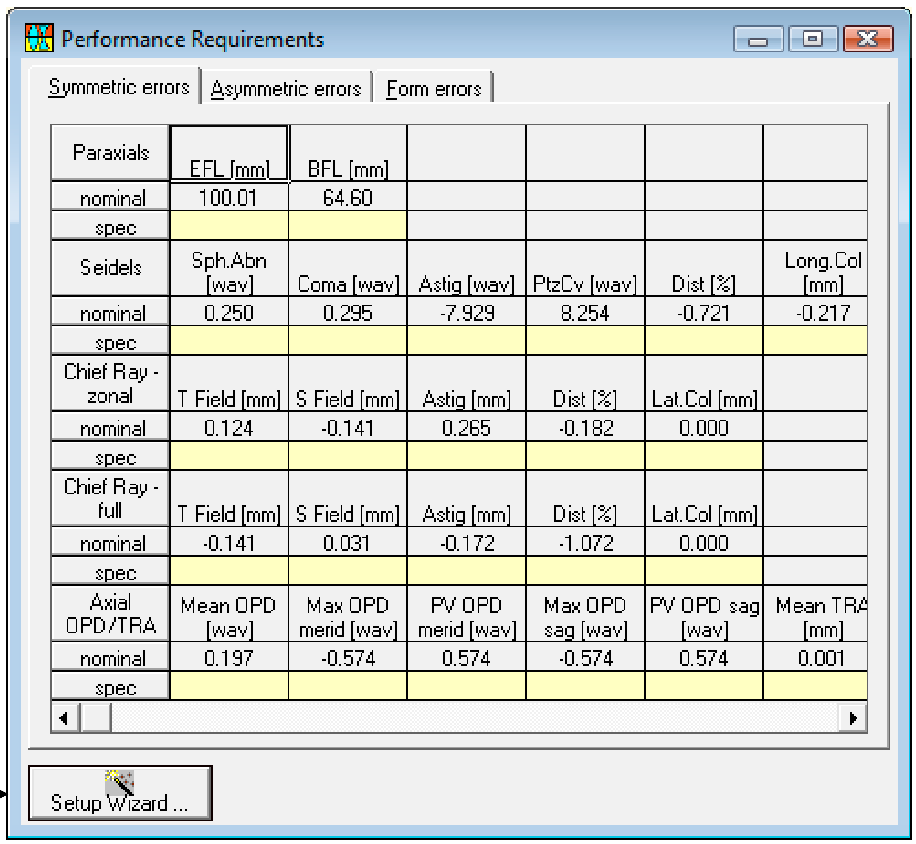
For example, if you have a diffraction-limited system with 0.1 waves of spherical aberration, you may require that the actual spherical aberration lie between 0.125 and 0.075 waves. The specification on spherical aberration is then ±0.025 waves.

You do not need to enter performance requirements to use WinLens Tolerancer!

However, there is a **major benefit** in entering requirements. The tolerance editors will predict the spread of the performance [statistically] for a batch of systems. This prediction is very quick [unlike the Monte Carlo simulations], and is updated each time you alter a tolerance.

These predictions are only made for the aberrations[6] you have selected, by entering specifications.

You may enter specifications for the key aberrations [chapter 10] for each of the three classes of manufacturing error [chapter 9]



Paraxials	EFL [mm]	BFL [mm]				
nominal	100.01	64.60				
spec						
Seidels	Sph.Abn [wav]	Coma [wav]	Astig [wav]	PtzCv [wav]	Dist [%]	Long.Col [mm]
nominal	0.250	0.295	-7.929	8.254	-0.721	-0.217
spec						
Chief Ray - zonal	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]	
nominal	0.124	-0.141	0.265	-0.182	0.000	
spec						
Chief Ray - full	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]	
nominal	-0.141	0.031	-0.172	-1.072	0.000	
spec						
Axial OPD/TRA	Mean OPD [wav]	Max OPD merid [wav]	PV OPD merid [wav]	Max OPD sag [wav]	PV OPD sag [wav]	Mean TRA [mm]
nominal	0.197	-0.574	0.574	-0.574	0.574	0.001
spec						

Setup Wizard helps to set specification for individual aberrations, using overall performance requirements

[6] In WinLens Tolerance you **cannot** directly specify spot sizes or MTF degradation. The reasons for this limitation are discussed fully in section 4.1 [Linear & Non-linear sensitivities]

Each class has a separate 'page' on this tabbed form. Click on the tab [at top] that you wish to inspect.
Each page has a spreadsheet, which is grouped into sets of three rows. Each set of three rows corresponds to one group of aberrations. The three rows contain:

- Aberration names and unit
- Nominal value
- Your requirement or specification

The last is optional: you do not need to fill in any of these. However those that you do fill in, will appear in the specifications section of the relevant tolerance editor [chapter 5]. This update is instantaneous if the editor is loaded.

There are different numbers of aberrations in the different groups.

The nominal value is included as a guide. If your optimised system has a nominal aberration of x, then you will probably want to enter a specification of y, where y is less than x, but not tiny in comparison.

It may be that the design criterion may be used directly. For example, the original specification may call for a focal length of 100mm ±2%. In this case you would enter 2.00, in the editable cell under EFL.

The various aberrations [see chapter 11] available are:

Error Class	**Aberration Class**	**Notes**
Symmetric	Paraxials Seidels Real Ray [axial, zonal, full field]	astigmatism, distortion & lateral colour
Asymmetric	Asym Seidels Real Ray [axial, zonal, full field]	Boresight, axial coma & linear astigmatism astigmatism, distortion & lateral colour
Form	Axial Fan TRA & OPD Zonal Fan TRA & OPD Full Field Fan TRA & OPD	mean & peak-valley values

Note that zonal and full field options are only available if sufficient fields have been defined in the lens file, by WinLens.

3.1 How to choose specifications

This is obviously crucial. We recognise that it is not obvious how to set sensible values for individual aberrations, when system requirements are almost always in terms of spot size or MTF.

Therefore Tolerancer has a wizard to help in this task. This wizard is launched by clicking on the 'Setup' button at the bottom of the specification form.

As you work through the wizard it will help convert these overall performance requirements into sensible specifications on the individual aberrations.
First, though, from years of experience, we have found that often, controlling a few key aberrations will keep the others under control. Typically, when making small changes to system, higher order aberrations are fairly stable, but the major changes are in the paraxial [efl & bfl] values and the Seidel aberrations.

So for the on axis field, managing Seidel spherical aberration is a very important method of maintaining the performance of a batch of systems.

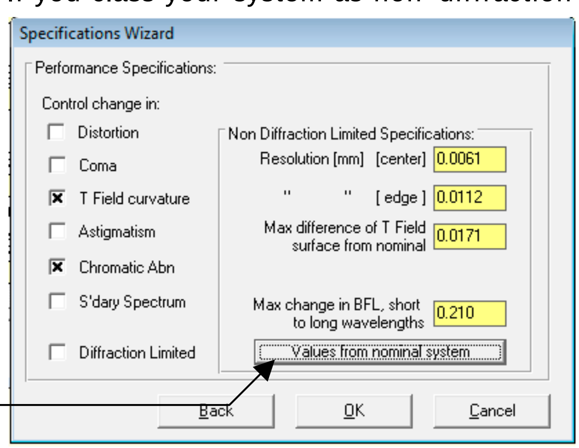
Off axis, seidel coma may be significant, but normally T field astigmatism varies much more than S field astigmatism. This could be controlled by the seidel astigmatism, but we prefer to use the real ray value [derived using the Coddington equations]

Distortion, by contrast, is often quite stable, and is therefore often kept within specification automatically when the other aberrations are controlled. However if simulations show that it is sensitive, then the allowable variation can be directly entered as a percentage.

3.2 The specification wizard

If you class your system as diffraction limited, then all you have to do is select which types of aberration you want to control. The wizard will then determine specifications based upon the quarter wavelength rule [with the exception of distortion!].

If you class your system as non-diffraction limited, then you have a bit more work to do. You will again need to select the type of aberration that you wish to control.



New tool – creates a starting set of specs based upon the performance of the nominal system.

You will also need to enter some values that define the overall performance of the system.

From these values Tolerancer deduces specification appropriate for the key individual aberrations, such as seidel spherical aberration. You can enter these values manually, maybe from the project documents.

Symmetric errors – spec for single aberration	**Obtained from:**
SI Seidel spherical aberration	amount of SI in waves for equivalent TRA[7] to equal ½ value of **'resolution [center]'**
SII Seidel coma	amount of SII in waves for equivalent TRA to equal value of **'resolution [edge]'**
T field curvature	**'Max difference of T field surface from nominal'**
Astigmatism	As for T field curvature
CI Longitudinal chromatic aberration	Amount of CI for equivalent longitudinal abn to equal ½ 'Max change in BFL'
CII Lateral Chromatic aberration	Amount of CII for for equivalent longitudinal abn to to equal value of **'resolution [edge]'**
CIII Secondary spectrum	As for CI
Asymmetric errors	
Axial coma	Amount of axial coma required to generate **'resolution' [center]**
Form errors	
Axial astigmatism	Amount of axial astigmatism required to generate **'resolution' [center]**

Alternatively, Tolerancer can generate an initial set based upon the performance of the nominal system [click the button marked 'Values from nominal system]. How the values are generated is described in the table ebelow.

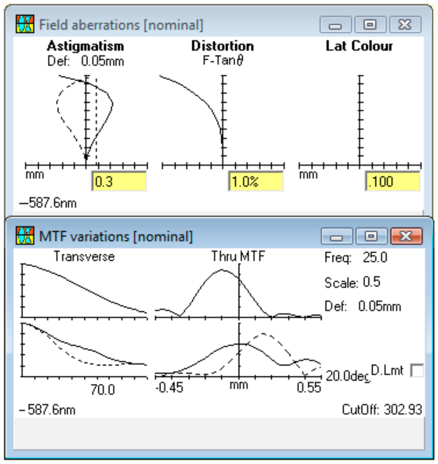
System performance value	**Obtained from**
Resolution [center]	RMS spot size [dia] on axis
Resolution [Edge]	RMS spot size at edge of field
Max difference of T field surface from nominal	±½ depth of focus[8] of system for circle of confusion = resolution[center]
Astigmatism	As for T field surface
Chromatic aberration	Change in BFL[long to short] wave
Secondary spectrum	As Chromatic aberration

There is an alternative simple method for setting the specification for T field curvature, which can also be used, and is now detailed.

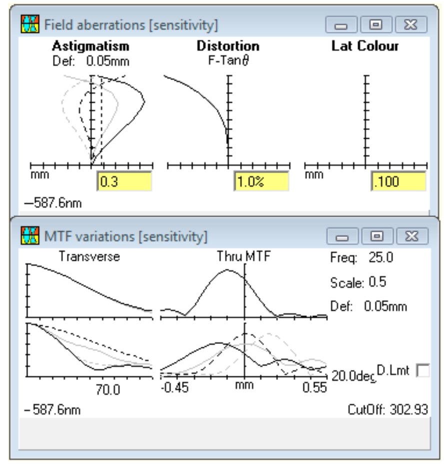
[7] TRA transverse ray aberration
[8] Depth of focus = effective f.nos x circle of confusion.
Eff f.nos can be read from the system parameter editor [aperture tag]. Circle of confusion, in this case, is taken as RMS spot diameter.

This is based upon simple inspection of the MTF curves. As a first order approximation, change in astigmatism produces a longitudinal movement in the peaks of the MTF curves.

Nominal system



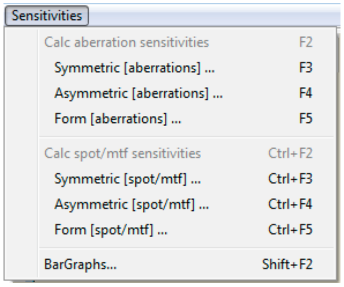
Perturbed system



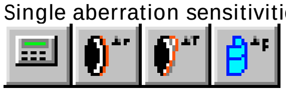
Therefore, look at the full field curves for the nominal system; in particular the thru focus curves. See what is the smallest distance the curves need to move in order for the MTF on the detector to fall to an un-exceptable level. This will then the specification. In this case a value of ±0.01mm is a reasonable start.

Once the specification for the single aberrations have been set, then you can edit the tolerances with some useful feedback. This can then be confirmed [or otherwise] by the Monte Carlo simulations. From the results of the simulations you may then wish to tighten or loosen the existing specifications, and add/remove new specifications.

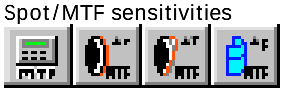
4. Sensitivity Analysis



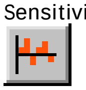
Single aberration sensitivities



Spot/MTF sensitivities



Sensitivity bar graph



Optical systems are defined by a number of parameters, such as curvature, separation and refractive index.

Some parameters are more sensitive [i.e. will generate larger drops in performance], when changed by a small amount, than others.

The optical designer must identify these parameters in order to assign them tighter tolerances. A sensitivity analysis[9] provides this information.

WinLens Tolerancer offers two sensitivity analysis[10] options:

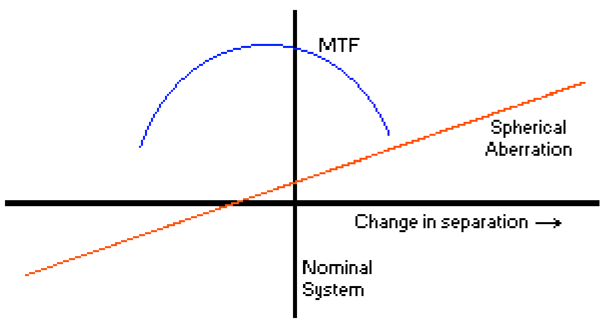
- Single aberration [paraxials, seidels, real ray astigmatism etc]
- Spot size and MTF

The former requires less ray tracing and is therefore quicker.

4.1 Linear & Non-linear Sensitivities

There is a further difference between the two options. Single aberrations tend to be linear functions of the design parameters [at least for the small changes we are considering. By contrast, spot size and MTF are often non-linear for the same changes.

This is illustrated in the sketch below, for a system which is nearly diffraction limited:



For single aberrations, only the first differential therefore need be found. In WinLens Tolerancer, we find all first differentials.

However for the MTF and spot size, we should include at least second differentials, including cross terms. It is the latter which is the problem, because of the sheer numbers. In a system with say 20 parameters, there will be about 200 cross terms[11] to evaluate. This is impractical, both in terms of time taken, storage required, and information overload for the user. Therefore the spot size/MTF sensitivity analysis is limited to the first differential and the homogeneous second differentials.

---

[9] A sensitivity analysis may be described by the following pseudo-code:
- Find performance of the nominal system
- For each parameter
    - Alter parameter by a set increment
    - Calculate performance of perturbed system
    - Store difference in performance from nominal
    - Return parameter to nominal value

Next parameter

[10] We use the finite difference approach, where the increment size is that of a typical tolerance. For each parameter we find the differences for positive and negative increments. In the sensitivity tables you can choose to look at either, or at the difference [non linearity]

[11] The cross terms might be the effects of changing separation X, at same time as changing radius Y, or index Z. as compared to the effects of changing those parameters individually.

You may wonder why we stress this difference. The reason is related to the statistical predictions. It is quite easy to predict the distribution of linear functions [such as EFL or spherical aberration] in a batch of lenses. It is not easy to undertake the same for non-linear functions such as spot size or MTF - especially if knowledge of the cross terms is not available.

Therefore in the tolerance editors and the requirements forms, you will see that you may only select single aberrations, i.e. you can place a requirement on focal length, spherical aberration or real ray astigmatism or distortion.

You cannot [unfortunately] directly place requirements [or get statistical feedback] on spot size or MTF.

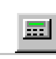
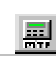
However, the Monte Carlo simulations do provide that information, and are available for spot diagrams and MTFs.

4.2 Running a sensitivity analysis

In chapter 10, you will see a detailed discussion of the different types of manufacturing error that will occur. In chapter 11, the key optical aberrations resulting from those changes are outlined.

When you run an analysis, WinLens Tolerancer works through each type of perturbation for all cases of that parameter, calculates the effects and stores the differences for the key aberrations.

It also calculates and stores the data necessary for the aberration plots [e.g. TRA curves, Spot diagrams etc].

Analysis	Toolbar ICON
Single aberration	
Spot size/MTF	

Once found, it is not possible [or necessary] to run a sensitivity analysis again until a new system is loaded.

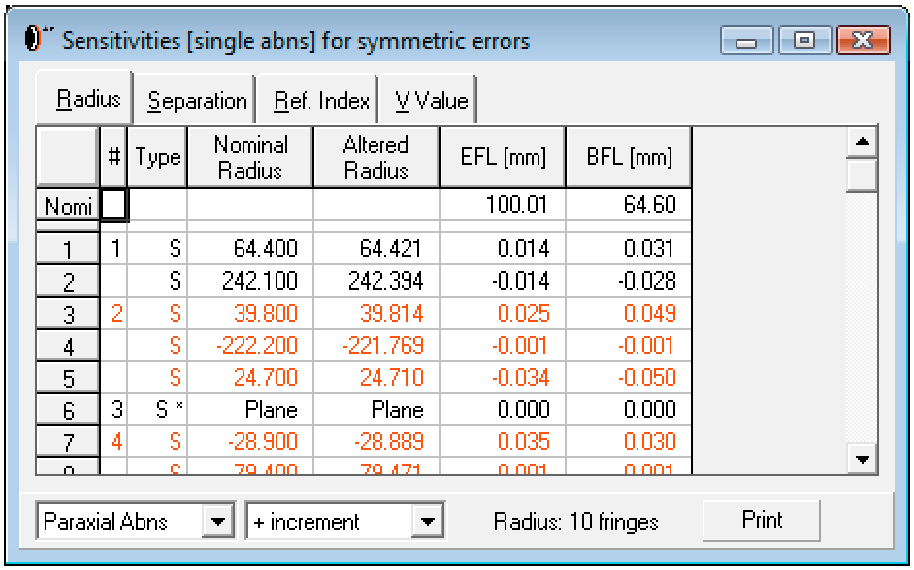
4.3 Display sensitivities: symmetric errors

Once you have run a sensitivity analysis, you may view the results of that analysis.

To inspect the effects of symmetric errors [changes in radius, separation, index or V- Value]:

Analysis	Toolbar ICON
Single aberration	
Spot size/MTF	

Since the results are displayed in two very similar forms, we will just discuss the details of the single aberration form.



This is a tabbed form, with each 'page' showing the results of a different parameter type. To inspect a different parameter type, simply click on the appropriate tab.

The sensitivities are shown in a spreadsheet, with one row per parameter. The top row shows the values of the aberrations for the nominal system.

In the left-hand columns you will see the nominal value of each parameter, and the perturbed value in the next column [the perturbation increment is shown in the bar at the bottom of the screen.

Since there are many possible aberrations, we display the sensitivities[12] for one class of aberration at a time. In this example we see the paraxial aberrations. To select a different class of aberration, choose one of the options in the drop down list at bottom left of the form.

For single aberrations sensitivity you may choose between paraxial, seidel and real ray [astigmatism & distortion for the extreme chief ray] aberrations.

---

[12] By default we display the differences in the aberrations resulting from the perturbation, rather than the differentials. This seems to give a clearer idea of the effects. However you can elect to show the differentials - select from the 2nd list

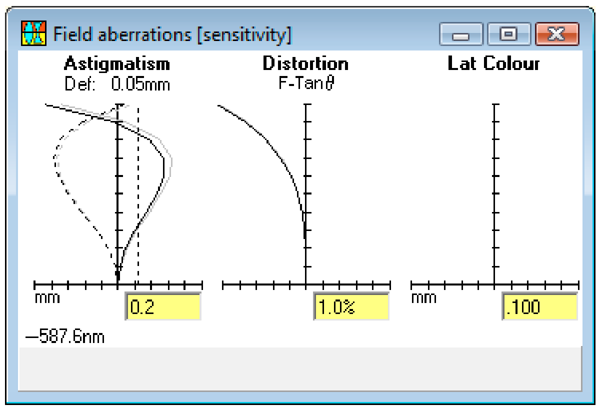
For spot size/MTF you may choose between axial, zonal[13] or full[14] field values.

You may also elect to see the data for the positive perturbation, the negative perturbation or the difference between the two. The latter gives an idea of the non linearity of that particular optical effect. Select the required option from the second drop down list at the bottom of the form.

In the table you will see a limited range of aberrations [those we have found to be significant]. You may also view the impact of any perturbation on the aberrations plots [TRA, Field, Spot Diagram, MTF etc].

- Make sure the relevant graph is loaded.
- Click on the row for the perturbation of interest

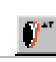
In the graphs you will then see two sets of curves, one for the nominal system [faint] and one for the perturbed system. These curves are overlaid, for ease of comparison.



Finally, you may obtain a printout of the sensitivities for the current parameter type, by clicking the ‘Print’ button at bottom right of the form.

4.4 Display sensitivities: asymmetric errors

To inspect the effects of asymmetric errors [tilt & decenter]:

Analysis	Toolbar ICON
Single aberration	
Spot size/MTF	

The forms showing the results of asymmetric perturbations ae vary similar to those for the symmetric perturbations, as described in the previous section. This being so, we will not repeat information already given.

There are six different types of perturbation listed [see chapter 10.2 for more information]. The single surface tilts and decenters are actually non-physical, but are included because it is useful to see which surfaces need special attention. This information may help in your choice of mounting surface.

[13] Zonal spot/MTF data is only available if you have set up the system in WinLens with 3 or more fields.
[14] Full field spot/MTF data is only available if you have set up the system in WinLens with 2 or more fields.

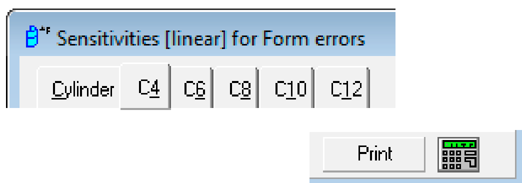
4.5 Display sensitivities: form errors

To inspect the effects of form errors [cylinder and symmetric irregularity errors]:

Analysis	Toolbar ICON
Single aberration	
Spot size/MTF	

A discussion on form errors is to be found in section 10.3. In the standard sensitivity analysis, only cylinder errors are assessed.

To see the impact of the symmetric irregularity or aspheric errors, you will need to start another sensitivity analysis devoted to these errors.



Select a tab devoted to one of the aspheric errors [C1[15], C2,..C5] and press the button at bottom right of the form. WinLens Tolerancer will then calculate the effects of the aspheric errors and display them in the spreadsheet.

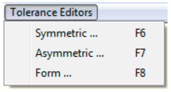
Note that when we tolerance such errors [section 5.3], you do not directly tolerance C1, C2 etc, since it is not known what combinations of these may occur in manufacture. Instead a tolerance may be placed on the maximum sag error [and possibly on the maximum surface slope[16] error]. These tolerances are then automatically distributed among the aspheric errors.

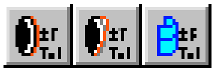
---

[15] C1, C2,..C5 refer to Zernike coefficients used for defining aspheric surfaces.

[16] From ISO 10110: slope errors are normally defined only for aspheric surfaces. However we have encountered systems where slope tolerances needed to be defined for spherical surfaces.

5. Editing Tolerances





Three tolerance editors have been provided so that you can enter/edit the tolerances: one for each error class.

Each editor is on a separate form. These forms also contain statistical feedback on the tolerances and various tools to help in the editing.

The tolerances defined by the editors are used in the Monte Carlo simulations [chapter 6].

5.1 Editing tolerances on symmetric errors

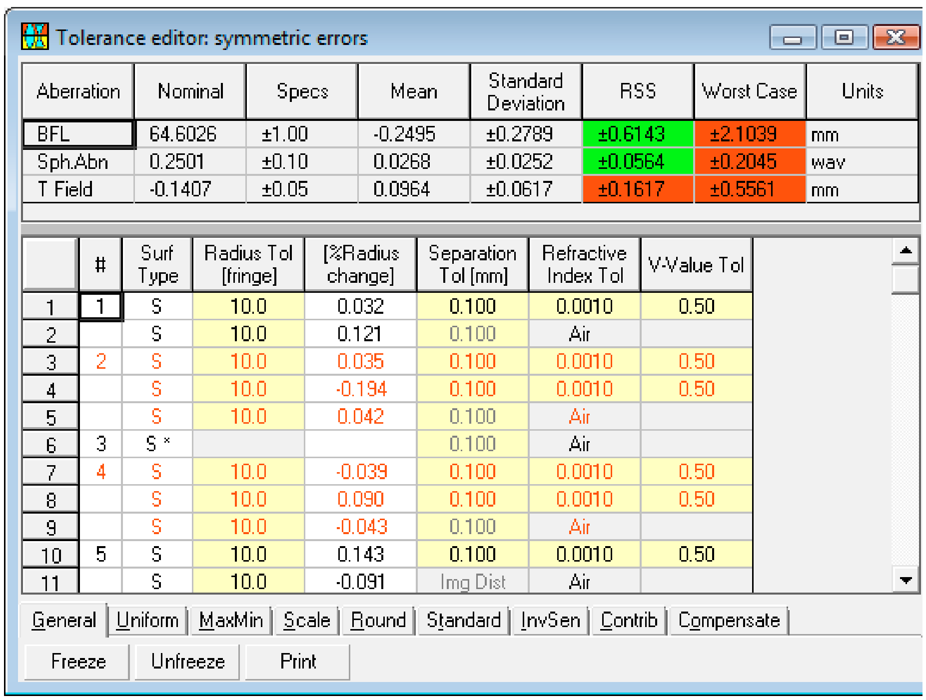
To load the symmetric tolerance editor, click on the button in the  toolbar or use the 'Tolerance Editor' menu.

This editor allows you to directly edit individual tolerances, or to use various tools[17] to control multiple tolerances. It offers rapid statistical feedback on the impact of any change.

Feedback

Editing

Tools



Aberration	Nominal	Specs	Mean	Standard Deviation	RSS	Worst Case	Units
BFL	64.6026	±1.00	-0.2495	±0.2789	±0.6143	±2.1039	mm
Sph.Abn	0.2501	±0.10	0.0268	±0.0252	±0.0564	±0.2045	wav
T Field	-0.1407	±0.05	0.0964	±0.0617	±0.1617	±0.5561	mm

	#	Surf Type	Radius Tol [fringe]	[%Radius change]	Separation Tol [mm]	Refractive Index Tol	V-Value Tol
1	1	S	10.0	0.032	0.100	0.0010	0.50
2		S	10.0	0.121	0.100	Air	
3	2	S	10.0	0.035	0.100	0.0010	0.50
4		S	10.0	-0.194	0.100	0.0010	0.50
5		S	10.0	0.042	0.100	Air	
6	3	S *			0.100	Air	
7	4	S	10.0	-0.039	0.100	0.0010	0.50
8		S	10.0	0.090	0.100	0.0010	0.50
9		S	10.0	-0.043	0.100	Air	
10	5	S	10.0	0.143	0.100	0.0010	0.50
11		S	10.0	-0.091	Img Dist	Air	

This form is split into three areas whose functions [editing, feedback and tools] are fully defined in the subsections below.

5.1.1 Tolerance spreadsheet

The tolerances for each parameter are displayed in an editable spreadsheet. To change a tolerance, simply position the cursor in the cell of interest, and enter the new value.

Note that beside the radius tolerance [in fringes] you can see the equivalent percentage change in radius of curvature.

Only glass spaces may be toleranced for index and v-value.

[17] The multi-level undo-redo facility is accessed through two icons on the main toolbar. 

5.1.2 Statistical feedback

If you have entered some specifications [see chapter 3], then the statistical feedback area at the top of the form will be active.

As we have explained, the spread of values for a particular aberration in a batch of system will be described by some probability distribution [often a gaussian]. It is possible to predict that distribution from a knowledge of the sensitivity of each parameter and the tolerance on each parameter.

This section shows the predictions for the distributions of each of the selected aberrations. The predictions are contain in a small spreadsheet with one row per aberration.

The predictions are updated whenever tolerances are altered.

Working from left to right, you will see:

- Aberration name
- Value of that aberration in the nominal system
- Specification [allowed variation in the aberration] you have entered in the requirements form
- Mean of the distribution
- Standard deviation of the distribution
- RSS[18] value
- Worst case[19] value
- Units for that aberration

As a useful guide, aim to keep the RSS value within the specifications. By contrast, it does not normally matter if the worst case exceeds the specifications, even by quite large amounts.

Note the use of colour coding on the RSS and worst case values. Red shows the value is greater than specification. Yellow for up to ¾ of the specification, and green for less than ¾ specification.

5.1.3 Editing tools

The tabbed section of the form offers many editing tools. To select a tool simple click on the appropriate tab.

5.1.3.1 General

You may ‘freeze’ or ‘unfreeze’ any tolerance or group of tolerances. Frozen tolerances will not be effected by any other editing tool [though they may be changed manually]. Frozen tolerances are indicated by a light blue background.

To freeze/unfreeze a group of tolerances, select the tolerances on the spreadsheet and then press the appropriate button.

---

[18] RSS value: root sum of squares. This is the standard deviation of the aberration distribution, **if** the magnitude of an error is always at the tolerance limit.

Normally errors will be less than the tolerance, so this is a very conservative value. Most systems will therefore lie within ±1RSS of the nominal value.

[19] Worst case value: This is the aberration expected when all errors are at tolerance limit, and all the effects add ‘constructively’ to produce the worst possible optical performance. This is an very unusual case; an equivalent would be throwing a handful of dice and getting all sixes.

If you tolerance to get the worst case within the specifications, you will normally require very tight tolerances. Such an approach is therefore very expensive.

Press the print button to obtain a printout of the current tolerances.

5.1.3.2 Uniform tolerances

You may set all the tolerances of a given type to a uniform value, e.g. set all radii to 5 fringes.

- Select the parameter type from the drop down list at the left
- Enter the desired value in the text box
- Click the Update button

5.1.3.3 Maximum/Minimum tolerances

You may set maximum and minimum values for the tolerances of a given type. Tolerances tighter than the minimum are increased, while those looser than the maximum are tightened.

- Select the parameter type from the drop down list at the left
- Enter the minimum and maximums in the text boxes
- Click the Update button

5.1.3.4 Scaling tolerances

You may scale all the tolerances of a given type, or all types, by some scale factor.

- Select the parameter type from the drop down list at the left
- Enter the desired scale factor in the text box
- Click the Update button

5.1.3.5 Rounding tolerances

As a result of using the inverse sensitivity tolerance distribution method [section 5.1.3.7], you will find that the tolerances have many digits, e.g. radius tolerance of 5.274 fringes. Since the workshop will ignore such precision, you may use this function to round the tolerances to more sensible levels.
You may round the tolerances of a given type, or all types.

- Select the parameter type from the drop down list at the left
- Click the Update button

5.1.3.6 Standard Tolerances

Workshops tend to have preferred tolerance bands. As a means of generating some starting point, you may elect to use one of these standard tolerances.

- Select the parameter type from the drop down list at the left
- Click the preferred standard from the option buttons
- Click the Update button

5.1.3.7 Inverse Sensitivity

This tool creates a set of tolerances which are in inverse proportion to the sensitivity of each parameter. Sensitive parameters will have tight tolerances, insensitive parameters will have loose tolerances. The tolerances will be scaled so that the RSS value [see above section 5.1.2: statistical feedback] is equal to the specification.

This tool only works on one aberration at a time. Selecting different aberrations will generate quite different tolerances.

You must have entered performance specifications on one or more aberrations for this method to be available [see chapter 3]

This tool works on all unfrozen tolerances, irrespective of error type.

- Select an aberration from the drop down list at the left
- Click the update button

If you have several key aberrations selected, you may want to use an iterative approach, controlling one aberration, freezing tight tolerances, and then repeating for the other aberrations.

5.1.3.8 Contributions

The impact of a given tolerance upon the statistical predictions is related to the product of the sensitivity and the tolerance. You may see the ‘contributions’ from each parameter for a selected aberration [as in the previous section, you must have entered some specification on one or more aberrations first].

Simply:

- Select an aberration from the drop down list at the left
- Click the update button

The tolerances in the spreadsheet will then be replaced by the contributions.

Look for the parameters with large contributions. If possible reduce the tolerances on these parameters, as this act will have a much larger impact on the aberration statistics than an equivalent tolerance change on a parameter with a small contribution.

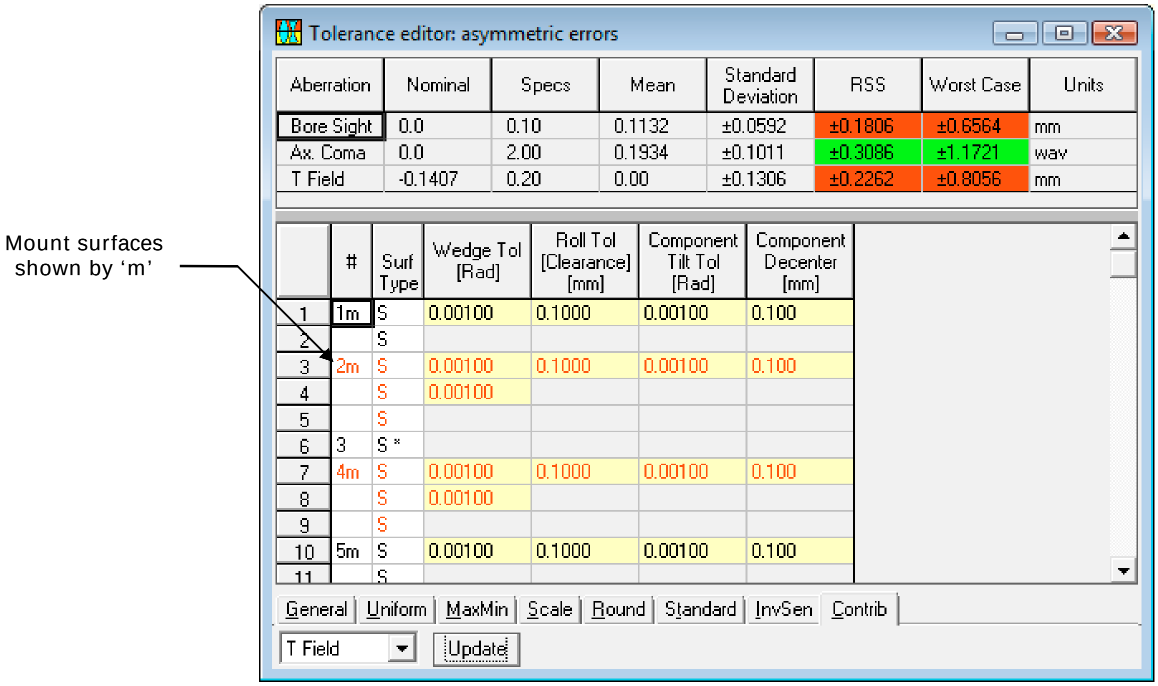
The tolerances will reappear when you touch the spreadsheet again.

5.1.3.9 Compensator [new v 2.1.3]

This tool allows you to select a compensator [adjust an air space to reduce the impact of the manufacturing errors]. This is described in detail in chapter 7.

5.2 Editing tolerances on asymmetric errors

The essentials of the asymmetric error tolerance editor are the same as the symmetric error tolerance editor. Therefore we will not repeat the detailed information given in section 5.1 on editing and the various tools.



There are two main points which should be made, concerning:

- Selection of mount surface
- Use of component tilt and decenter

5.2.1 Selection of mount surface

As discussed in section 10.2, the choice of mount surface for a component may be important. The mount surface for each component is indicated by a letter 'm' in the left most column. To change the mount surface for a component simply click in another row [that relates to the component] in that column.

It is not usual to mount a component off an internal surface[20]!

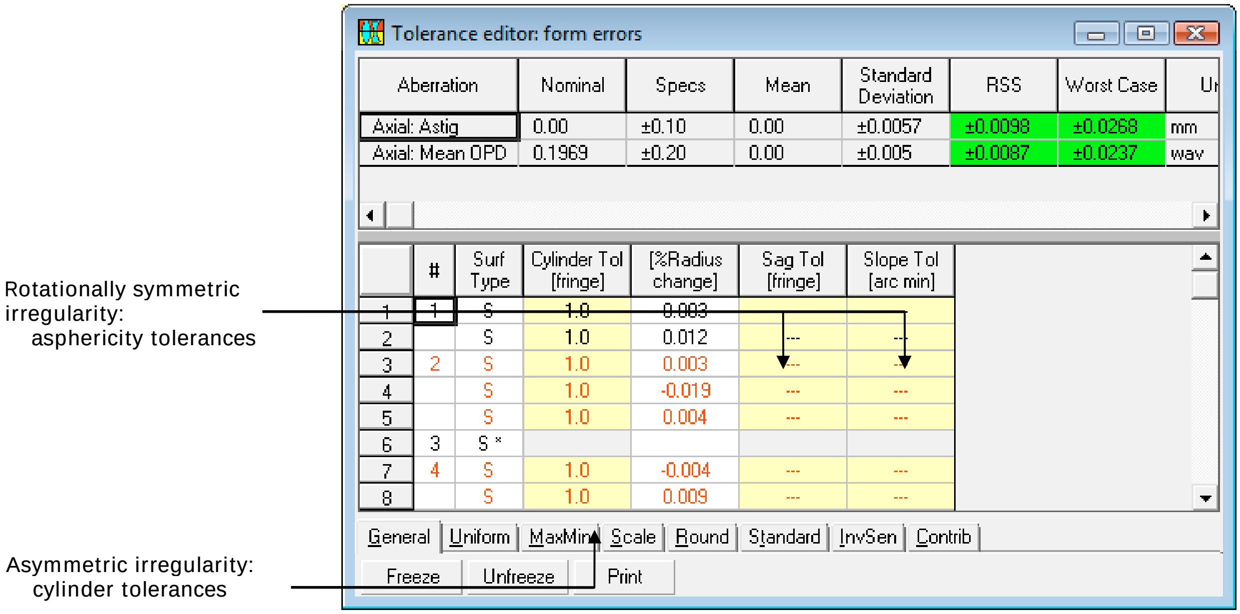
5.2.2 Use of component tilt and decenter

In the symmetric tolerance editor, it is not realistic to set any tolerances to zero. However the lens mount may be such as to allow some asymmetric errors to be ignored. For example, if all components are mounted in a single bore, then component tilt and component decenter may be set to zero.

[20] Obviously internal surfaces can only occur in components made up of two or more elements.

5.3 Editing tolerances on form errors

The essentials of the form error tolerance editor are the same as the symmetric error tolerance editor. Therefore we will not repeat the detailed information given in section 5.1 on editing and the various tools.



The tolerance spreadsheet needs some further explanation.

The tolerance columns may be split into two groups:

- Cylinder tolerances [asymmetric irregularity]
- Sag tolerance and slope tolerance [aspheric irregularity]

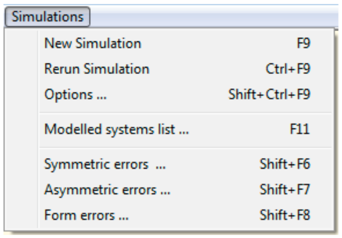
The former are always controlled [normally at a fraction of the curvature tolerance].

The later are normally only used for aspheric surfaces, and as such are only entered by the user [i.e. defaults of zero]

As described in the section on form sensitivity [4.5] and form error [10.3], no one really seems to know what is the functional form of aspheric irregularity. In WinLens Tolerancer we have chosen to model this by the addition of small amounts of asphericity, as defined by the Zernike coefficients [rather than the simpler standard power series terms].

The sag and slope tolerances may be specified. These tolerances are then equally distributed among the Zernike terms, both for statistical predictions and Monte Carlo simulations.

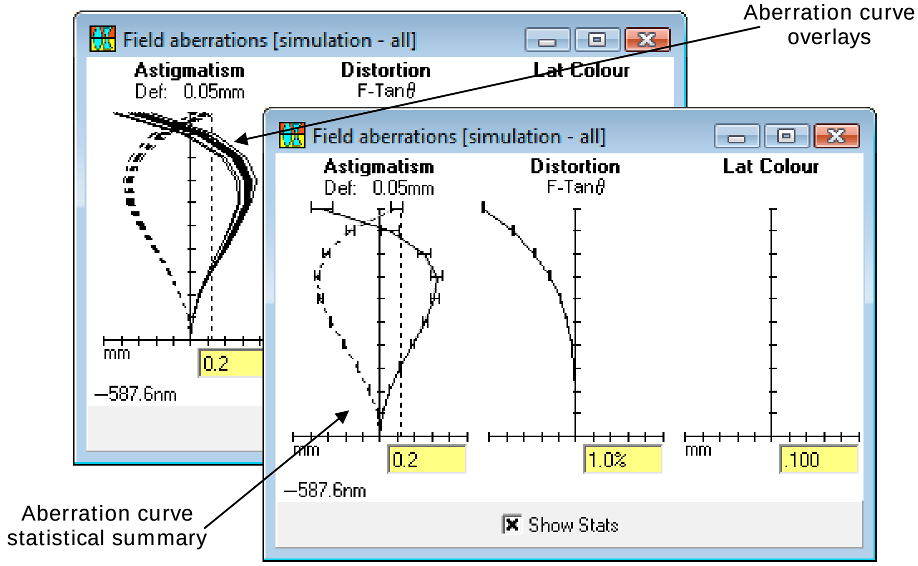
6. Monte Carlo Simulations



In order to test the tolerances selected, WinLens Tolerancer uses statistical predictions and also Monte Carlo simulations.

The simulator will create a batch of lenses, with errors obtained from appropriate probability distributions. The maximum size of the errors are set by the tolerances.

The program then analyses each system in turn and stores the results for analysis and/or 'replay'. As well as numerical values [shown in the modelled system list [section 6.3], the simulation will build up overlays of the aberrations curves for all systems, and also statistical summaries of the same.



6.1 Running simulations

To run a fresh simulation simply click the icon in the toolbox, or use

the 'New simulation' option in the 'Simulations' menu. This will start the simulation. Progress of the simulation is shown by the progress bar on the bottom of the main WinLens Tolerancer form.

You may abort the simulation at any time. Simply press the 'abort' button in the floating box which appears at the lower middle of the screen.

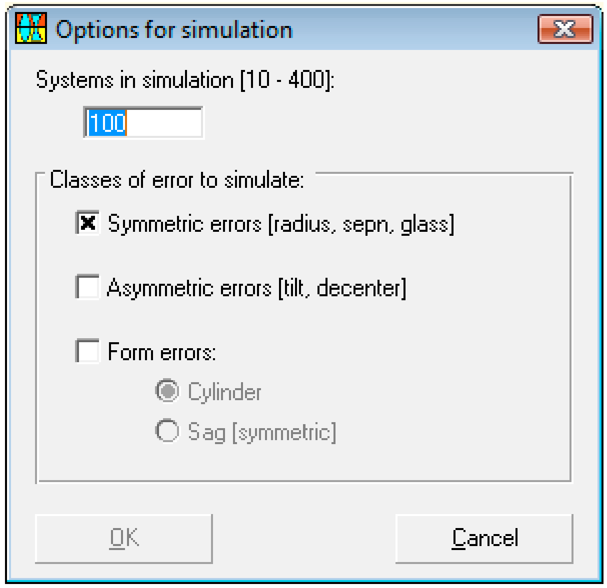
If you wish to re-run the simulation with different options [next

section], such as another class of error, then use 'Rerun' option in the simulation menu.

6.2 Simulation options

Initially, the simulation is for a small number of system, and only

symmetric errors. If you select the 'Options...' option from the simulations menu, or click this icon, the simulation options dialog will appear.

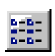


You can specify the classes of aberration you wish to simulation, and the number of system you wish to model.

Obviously, more systems take longer to simulate.

Finally, note that you cannot simulate cylinder and aspheric irregularity [sag] errors at the same time, in WinLens Tolerancer.

6.3 Modelled systems list

A list of the systems in the simulation is available. This can be  accessed by toolbar icon, or by selecting the 'Modelled systems list' from the 'Simulations menu. This list has three functions:

- display levels of the key aberrations in these systems
- allow user to re-inspect performance curves for any or all system in the simulation
- allow user to inspect errors in any one system in the simulation.

Click on column headers to sort by the values of that aberration

Top row show nominal aberrations.

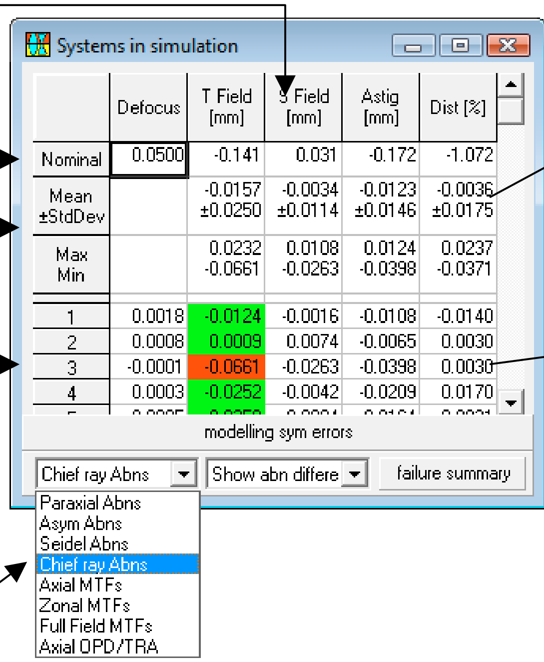
Next show shows stats for simulation

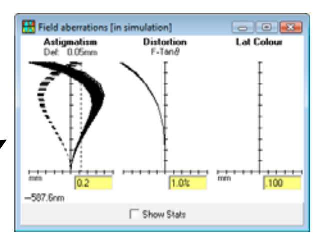
Each row represents one system.

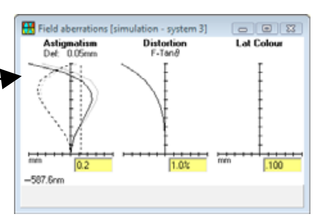
Aberrations for that system shown in row.

Click on row to see performance of that system.

Select type of aberrations displayed from drop down list







6.4 Linked aberration plots

While the simulation is running, all aberration curves are recorded for all systems. If any of these graphs are loaded, you can see the simulation results being built up as the simulation progresses. If you load any graph after the simulation is complete you can still see the results of the simulation.

If you click on a system in the modelled system list [section 6.3 above], you will see the aberration curves for that system, and the nominal system [drawn faint]

6.5 Linked error displays

You may inspect the errors used in any system in the simulation. Make sure that the simulation list [section 6.3 above] is loaded. Then pull down the 'Simulations' menu and select the 'Symmetric errors...', 'Asymmetric errors...' or the 'Form errors...' option..

Alternativly use the toolbar buttons shown here WinLens Tolerancer will then load a spreadsheet showing the appropriate errors for the 'current system'.

To inspect the errors for another system, simply click on a system in the modelled system list form.

[*V2.2.2*] These forms can now be also used to enter errors directly and see the impact on the various graphs. This is discussed in full in chapter 9.

7. Compensators

"Com·pen·sate. v -s[fr L compensatus, (past part of compensare)]…
3:a to provide with means of counteracting variation
3:b to neutralize the effect of (variations)"

Webster's third New International Dictionary

In the world of tolerancing, a 'compensator' is some action applied to an assembled system to counteract the effects of the manufacturing errors.

The most obvious example is that of refocusing. The various errors in a particular system will mean that the focal length/back focus of the system will not be at the nominal position. If the detector is placed at the nominal back focus, then the image will be more of less blurred.

One possible approach is to tighten up the tolerances. This will reduce the errors, and therefore the amount of movement of the back focus.

However this could be very costly, and may not be even necessary! If the detector is just to the actual back focus position, for that lens, then the image will often regain clarity, and tighter tolerances are not needed.

In some cases simple refocusing may not be possible, or may not be enough. Besides changing paraxial values, manufacturing errors will alter the aberration balance of the lens, often changing field curvature or distortion. Neither of these can be corrected by a simple refocusing. As we have said before, tighter tolerances would resolve the problem, but could be expensive.

The solution is to alter a construction parameter in that lens, in order to correct the changes in, say field curvature, induced by that particular set of manufacturing errors. The changed parameter is known as a parameter.

Clearly, neither regrinding components [to change thickness or ccurvature] nor changing materials is practicable, so changing air space thickness is the compensator type allowed in Tolerancer.

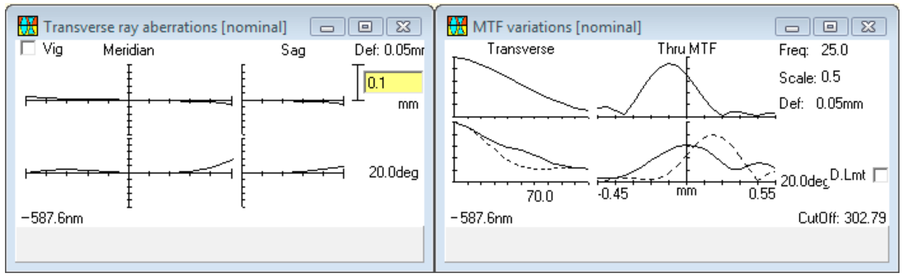
In particular, you may either alter the thickness of a single air space, or you may slide a component[s] between two airspaces.

Once selected, Tolerancer models the effects of the compensator in the Monte Carlo simulations. On top of this, Tolerancer has tools to help select a 'good' compensator.

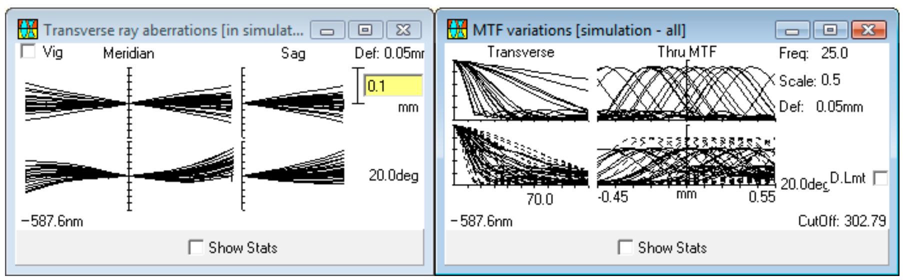
In the next section, we will illustrate the effect of a compensator, and in the following section we will look at how to apply a select a compensator.

7.1 Compensator example

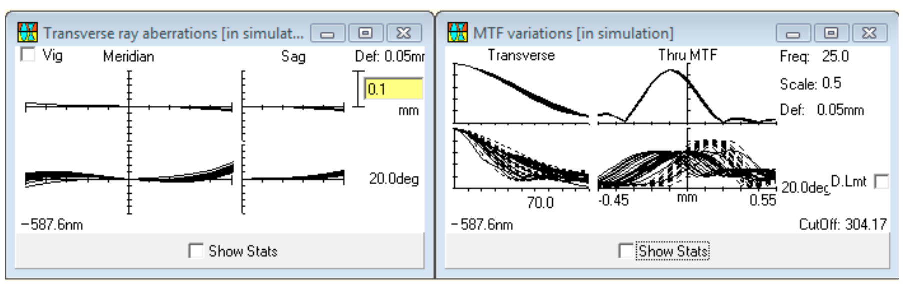
We will start with the example file WLDG001.SPD, using the default set of tolerances [standard loose values] Here we see the nominal system MTF and TRA curves:



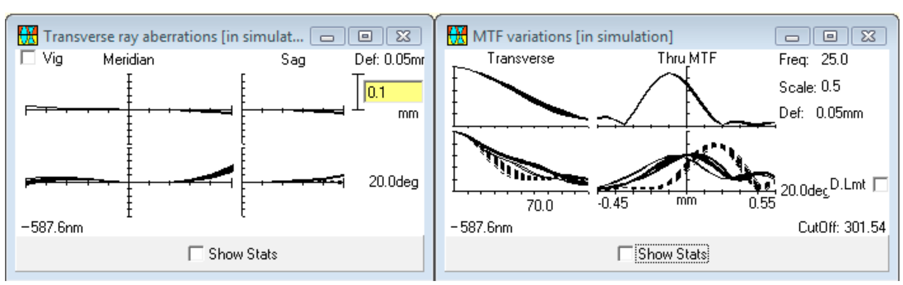
We will now run a batch of 20 systems, with the detector held at a fixed distance [nominal value] from the rear lens.



You can see clearly that the real best focus position is always moved away from the nominal. So now lets try a simple refocus.



That is much better – at least on axis. However off axis the T field is showing large variations. So now we will use one of the central air spaces to correct the variation in T Field astigmatism.



7.2 Defining a compensator

At present there are two ‘compensators’ available in Tolerancer: refocusing[21] and air space adjustment. In this section we will deal with air-space adjustment.

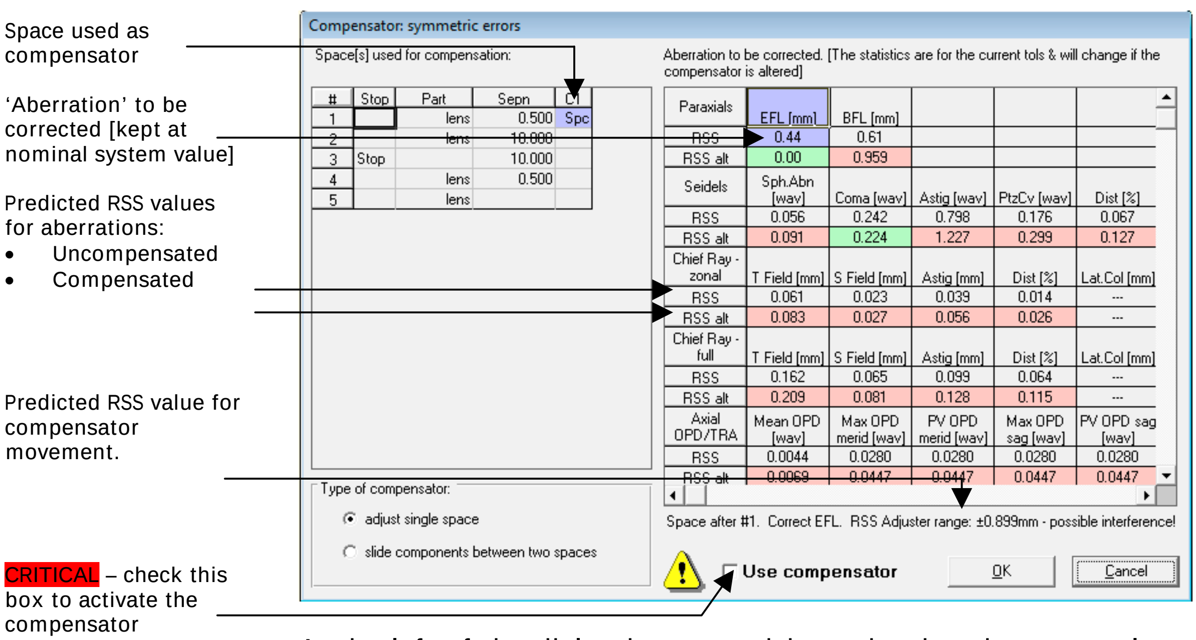
We need to select a space[s] to be adjusted, and we need to select an aberration to correct.

The choice of aberrations is restricted to those which are [roughly] linear[22] with error. By accepting this limitation, we can statistically predict:

- ranges of other aberrations
- range of movement of the compensator

These pieces of information will help us select ‘good’ compensators, i.e. those which do not make the spread in other aberrations get larger, and have a ‘sensible amount of movement. By sensible, we mean that the movement is not too large [millimeters or more], or too small [sub-micron]. A really good compensator would reduce the variation in all aberrations simultaneously!

Load the symmetric tolerance editor. Click on the ‘Compensate’ tab at the bottom right of the editor. Click on the ‘Define’ button. Tolerancer will load the dialog shown below.



At the left of the dialog is a spreadsheet showing the current lens. The space to be used as a compensator is shown in column C1 [at right of this spreadsheet] and is highlighted in blue. To change the compensator, simply click in another cell.

[21] Refocusing can be specified in the project options [from the main menu, click on 'Options' and select the 'Project options' option]. You can select refocusing from among the various options which control the location of the detector plane during simulation.
[22] The reasons for this have been discussed elsewhere in the manual [sections 4.1 & 9.1] when looking at the statistical predictions

If you have chosen to slide components between airspaces [option box at bottom right of dialog], then another column C2 will appear, showing the second space to be used as compensator. All components marked with the vertical | symbol will be slidden en block. In this case, the space after component 1 and the space before component 5 are 'linked' and components 2,3 & 4 are moved, without disturbing the global location of component 5.

#	Stop	Part	Sepn	C1	C2
1		lens	0.500	Spc	
2		lens	10.000	|	
3	Stop		10.000	|	
4		lens	0.500	|	Spc
5		lens			

At the right of the dialog, you can see the 'aberrations' or optical effects that can be corrected[23]. The selected aberration is also highlighted in blue.

Paraxials	EFL [mm]	BFL [mm]			
RSS	0.44	0.61			
RSS alt	0.79	0.724			
Seidels	Sph.Abn [wav]	Coma [wav]	Astig [wav]	PtzCv [wav]	Dist [%]
RSS	0.056	0.242	0.798	0.176	0.067
RSS alt	0.057	0.382	0.320	0.260	0.148
Chief Ray - zonal	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]
RSS	0.061	0.023	0.039	0.014	---
RSS alt	0.009	0.004	0.009	0.030	---
Chief Ray - full	T Field [mm]	S Field [mm]	Astig [mm]	Dist [%]	Lat.Col [mm]
RSS	0.162	0.065	0.099	0.064	---
RSS alt	0.000	0.018	0.018	0.127	---

To select an aberration for correction, simply click on its name!

Under each aberration, we see the statistical prediction of the range [RSS] of that aberration [given the current set of tolerances], for the system without compensation.

Underneath that we see the RSS value for that aberration when the compensator is active. The back ground to this value is colour coded:

- Green – RSS value is less than uncompensated RSS
- Yellow – RSS value up to 10% greater
- Red – RSS value over 10% greater

In this way we can see at a glance what impact correcting for a given aberration has on the other effects. An ideal compensator would correct everything else at the same time.

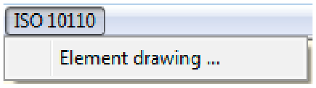
However we also need to see if this compensator is sensible. If the required movement is too small [say less than a few microns], then it will be difficult to achieve accurately. If the required movement is too large, then we may get mechanical collisions, and the linear basis of this prediction may break down.

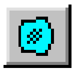
To help in this process, a predicted RSS value for the movement required is shown under this spreadsheet.

[23] By corrected, we mean returned to the level of that aberration as found in the nominal system. We do NOT mean set to zero!

8. ISO 10110 Drawings

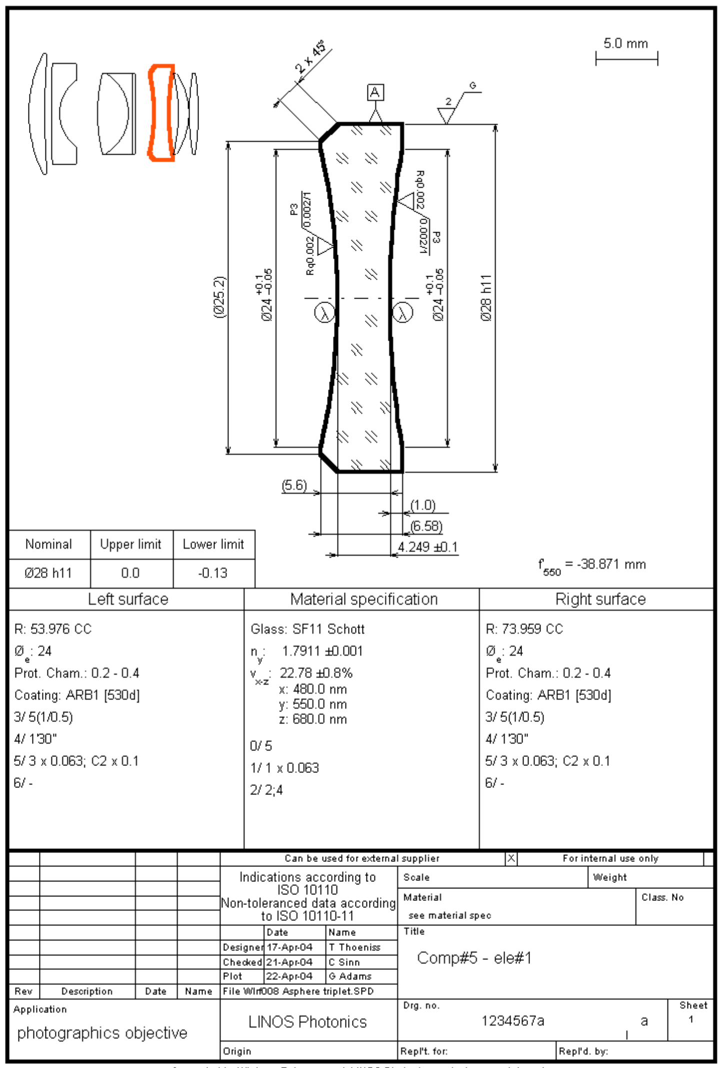
8.1 Introduction





WinLens Tol can now [*v2.2.1*] generate engineering drawings for individual lens elements and for cemented components according to the ISO 10110 standard part 10.

You can enter all necessary ISO tolerances manually, or you can choose to use values defined in the main tolerance editors [chapter 5]. This topic is discussed in section 8.7.



WinLens generates sensible defaults, but you can customise tolerance values, layout and appearance to a high degree. Because there are many points that should be mentioned, the following page contains an overview table.

We assume that you are familiar with ISO 10110. The following notes are not a tutorial on ISO standards!

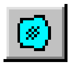
Key point summary:

Item	Notes	Section
ISO editor	**Editor form – various sections**	**8.2**
Preferences	Options applied to all drawings	0
Language	English, German or user supplied text on drawing	8.2.1.1
Options	Orientation/footer style/component part list	8.2.1.2
Layout	Show/hide main sections of drawing + location	8.2.1.3
Footer	Simple footer – location of each sub section	8.2.1.4
Logo	User supplied bitmap, plus location on drawing	8.2.1.5
Font	Font to be used, plus font size	8.2.1.6
Copying tolerances	How to copy tolerances from one surface/element to one, some or all other surfaces/elements	8.2.2
Default tolerances	How to setup & apply default tolerances to one, some or all other surfaces/elements	8.2.3
ISO preview	**Preview form and its utilities**	**8.3**
Standard symbols	Standard auto-drawn thickness & aperture dimensions, plus datum/coating/polishing symbols, and adjusting their location & length with sliders	8.3.1
User drawn items	User drawn/editable lines/text/ISO symbols	8.3.2
Creating	Using the toolbox to draw on the preview	8.3.2.1
Editing	How to edit user drawn items	8.3.2.2
Linestyles	Line thickness/style/arrows for user drawn lines	8.3.2.3
Zoom/pan	Various zoom options + panning	8.3.3
ISO output	**Various methods of reproducing drawing**	**0**
Printer	to printer [high resolution]	8.4.1
DXF	to a dxf file [autocad compatible]	8.4.2
Bitmap [BMP]	to a bitmap file	8.4.3
Element drawings	**Items specifically related to elements**	**8.5**
Surface	radius, aperture, coating + 3/, 4/, 5/, 6/ & note	8.5.1
Aperture, edge & chamfer	meaning of the different apertures, making the glass block bigger and defining drawn chamfers	8.5.1.1
Aspherics	aspheric elements have an extra drawing	8.5.1.2
Material	material, n & V, 0/, 1/ & 2/ & note	8.5.2
General	Details for footer	8.5.3
Cemented comp. drg.	**Items specifically relating to cemented lenses**	**8.6**
Component tolerances	Data for drawing/part list & tolerance table	8.6.1
General	Details for footer	8.6.2
Using tolerances from main program	**Notes on application of tolerances previously defined in the tolerance editors**	**8.7**

All ISO data is now saved in the tolerance files [.TOL]

You can enter all tolerances manually, or you can choose to use values defined in the main tolerance editors [chapter 5]. This topic is discussed in section 8.7.

8.2 ISO editor



[button on main tool-bar]

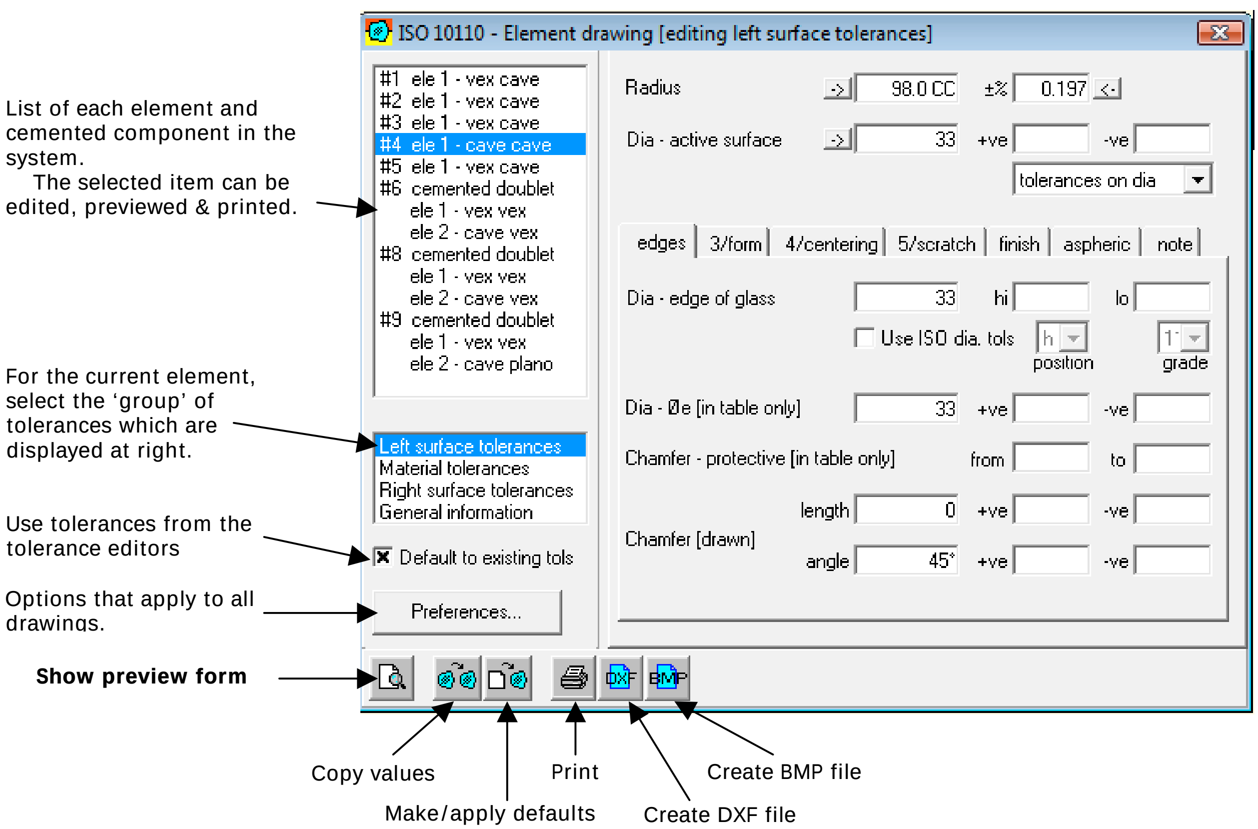
The ISO editor is a new addition [v2.2.1] to Tolerancer. From it, you may:

- select which element or component is to be drawn
- check/define tolerances & notes for the drawing
- select your drawing preferences
- copy tolerances from one surface/element to another[s]
- apply default tolerances to one or more surfaces/elements

The system is broken down into elements and cemented components[24]. These items are then listed for you to select one to edit/draw.

Each element has many items which may be defined; for ease we have collected them into related groups ['left' surface, material, 'right' surface & general]. These 'groupings' are listed under the element list. Select the 'grouping' of interest. The tolerances & values for that 'grouping' are shown at right.

Even when we just look at a single grouping, there are still many items. So we use a tabbed interface to contain the different items. Each tab contains a logically related set of items.



We strongly suggest that you also load the preview form – this is updated whenever you make a change to the editor.

8.2.1 Preferences

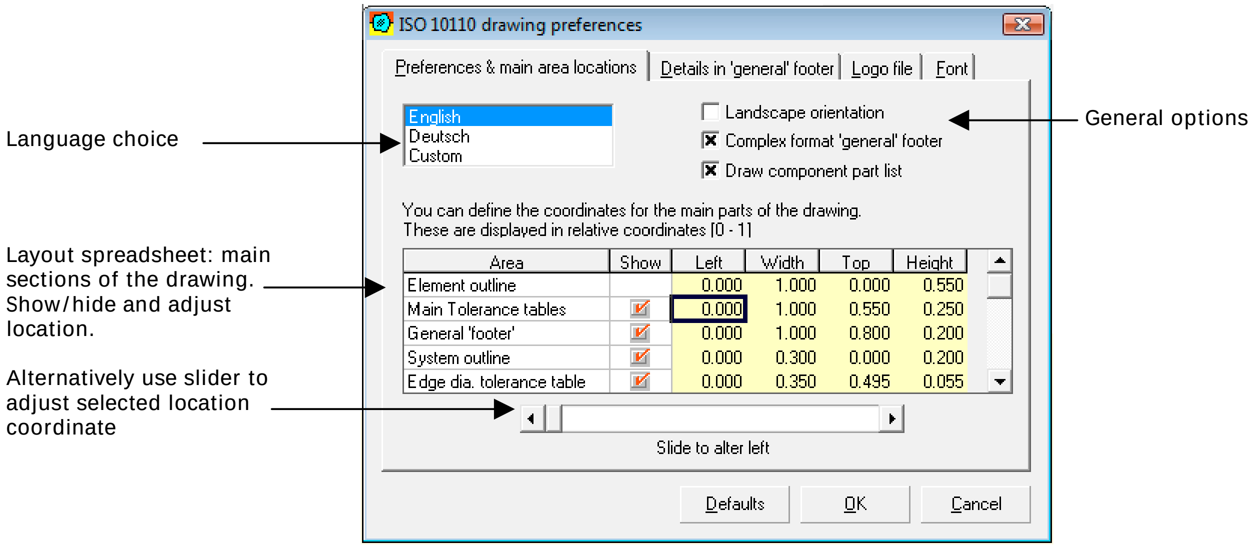
The preferences [accessed via 'Preferences...' button at mid/lower left of editor] apply to all drawings.

---

[24] Elements and cemented components have different drawing styles – a cemented component is made up of two or more elements – and is an assembly drawing

When you click this button, a tabbed dialog is launch. We will work through the tabs one by one.

When any change is made the preview is updated without the dialog closing – this makes it easy to see if the change is 'good'.



8.2.1.1 Language

[first tab] You may choose the language for the standard phrases on the drawing. These may be in English, German or user supplied.

The user-supplied phrases are held in the 'ISO10110UserLang.txt' file in the 'UserData' sub folder [this is created when you first run Tolerancer]. The file contains a list of the English phrases and a space for your replacement. If there is no replacement then the English is used.

8.2.1.2 Options

[first tab] There three check boxes, which control the following options:

- page orientation – portrait or landscape
- footer style – simple [10 rectangles] or complex [as shown on previous page]
- component part list – show or hide. Only applies to cemented component drawings.

8.2.1.3 Layout

[first tab] The drawing is divided into a number of major elements or sections, e.g. lens outline, tolerance table, footer, etc. These sections are listed in a spreadsheet. You can choose to show or hide any of these, by checking the box in the second column.

You can also adjust the size and location of the sections within the drawing. The spreadsheet contains the relative values of left, top, width & height of each section. You can type the desired value or use the slider beneath to adjust.

8.2.1.4 Footer

[second tab] This spreadsheet is only visible if the 'simple' footer [section 8.2.1.2] has been selected. You can define the location of each of the 10 subsections within the simple footer area.

8.2.1.5 Logo

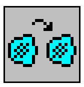
[third tab] You may select a bitmap which will be displayed on all drawings. Typically this will be your company logo. The bitmap may be in BMP, GIF or JPG format. [To alter its location on the printout/preview see section 8.2.1.3]

Logo bitmaps are NOT shown in the DXF [section 8.4.2].

8.2.1.6 Font

[fourth tab] You may select a single font for your drawing from the list on your PC. You may also choose the point size for the main text and a few key headers. The main text size will also control the size of the ISO symbols [standard and user drawn].

If you output to a DXF file [section 8.4.2], the font may be quite different. DXF files do not seem to support True Type files, and the default AutoCAD font is rather inflexible!



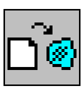
Copy function button on ISO editor

8.2.2 Copying tolerances

To save time/effort there is a powerful tolerance copy function available. When clicked, the copy dialog is displayed. You select:

1. the ‘source’ of the data [either the current element, or one of its surfaces]
2. data to be copied [check the options that you want to apply]
3. target of the ‘copy’. This could be the other surface in element, some selected elements or all elements in the system.

Note that lens system parameters [e.g. radius, separation, material or apertures/chamfer dimensions] are NOT copied!!



Default function button on ISO editor

8.2.3 Default tolerances

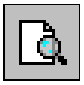
Frequently you will want to apply one of several sets of standard values. Tolerancer has some hardwired sets in, but you can also create multiple sets of your own defaults.

Applying defaults: similar to the copy function. You select:

1. The default to be applied - either one of the hard wired sets or one of your own [see below].
2. data to be copied [check the options that you want to apply]
3. target of the ‘copy’ operation. This could be other surface in element, some selected elements or all elements in the system.

Creating defaults: This is a two stage process.

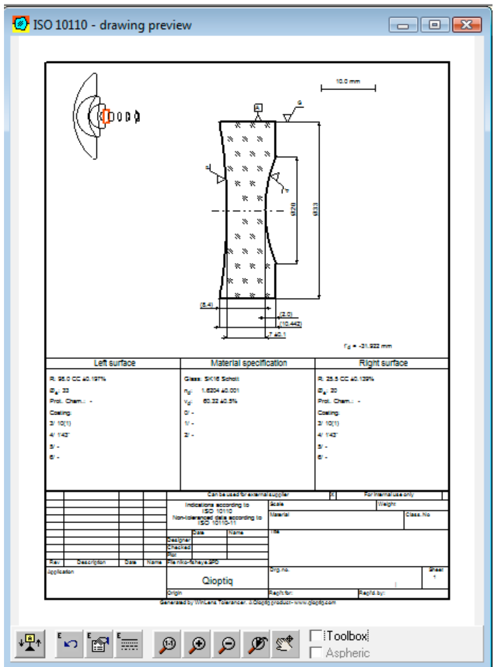
1. Load a system, select an appropriate element and manually define the default values – either for a single surface or for the entire element [both surfaces & the material].
2. Load the default dialog. Decide whether you want these values to be to be defaults for a surface only or for an entire element. Select the appropriate option and then click the ‘add tols to list’ button. You will then supply a name by which that set will be known. The new default set is recorded on your hard disk for future use.



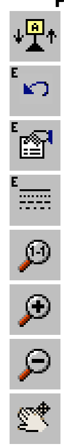
Load preview button on ISO editor

8.3 ISO preview

The preview form enables you to view, adjust and 'paint' on the drawing for the selected element or cemented component. The preview form is automatically updated whenever you make a change to the values displayed in the main ISO editor.



Preview form buttons



adjust standard symbols

undo last 'paint'

edit/move painted items

line styles for paint lines

return to full zoom

zoom in

zoom out

enable/disable panning

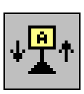
You can locate and resize the preview form where you find it most convenient.

At the bottom of the preview form are a range of buttons.

These allow you to adjust the standard symbols, edit user drawn items, change line styles, zoom

There are also two check boxes which allow you to show the paint tool box and to view the aspheric page[25].

8.3.1 Standard symbols



Edit standard symbols on preview form

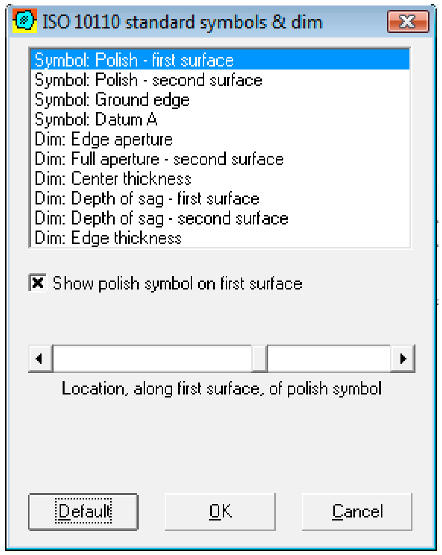
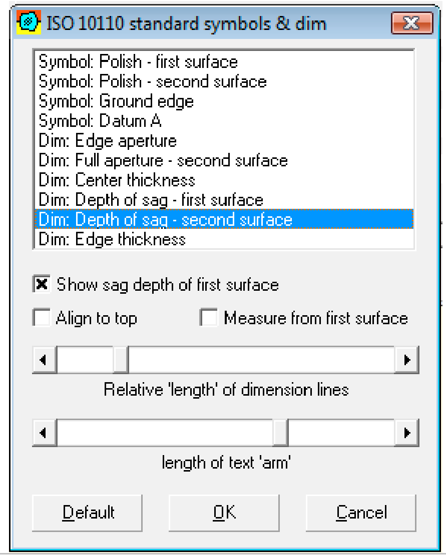
When an element or component is first drawn, a number of 'standard' items are drawn automatically. For element drawings these include:

- thickness, aperture & sag dimensions [as appropriate]
- datum[s]
- polish symbols
- grinding symbol [on element edge]
- coating symbols [as appropriate]

The default location of these is usually quite reasonable. However you may find some overlapping or wish to move them for some reason or other.

[25] Naturally this check box is only available if the selected element has one or two aspheric surfaces.

Click on the standard symbols button at bottom left of the preview form. You will see a dialog with a list of the standard symbols. Click any one item to edit it.

symbols	dimensions
	
Polish/grind/datum symbols: - Slider to move symbol round appropriate surface	Aperture/thickness/sag dimensions: - Slider to extend dimension lines - Slider to extend 'length' of text arm

As you move the slider, so the preview will be updated immediately so that you can easily get the best location.

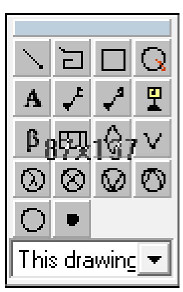
When you have finished, click OK to accept the changes, or Cancel to undo them.

8.3.2 User drawn items

You can draw or paint text, lines, rectangles and a range of ISO symbols. These painted items can belong to a single drawing, all drawings for a lens or even for all drawings. Once created, painted items can be edited or deleted.

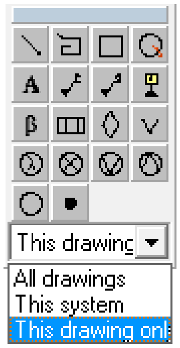
8.3.2.1 Creating

Access to the painting items is via a toolbox. To see the toolbox, simply check the 'toolbox' checkbox at bottom right of the preview form.



The toolbox contains icons representing each text box type.

To use a particular type, simply click the icon and then click on the preview at the desired point. Some tools [lines, boxes, circles] require you to click one or more further times to define the extremes of the drawn item. For other items a dialog will appear to obtain further information from you. For example, the text tool dialog allows you to enter text, font size and text orientation]

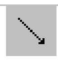
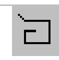
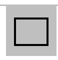
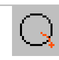
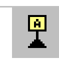
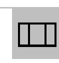
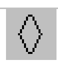
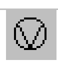
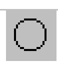


By default, these painted lines only appear on the current drawing. However, by selecting from the drop down list, you can choose to have items defined for:

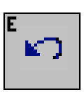
1. current drawing only [default]
2. all drawings for this system
3. all drawings

The later option should only be used if you are setting up some permanent 'pattern'. Any painted items defined under 1 or 2 are saved in the tolerance file.

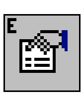
The following table defines the various painting tools and lists what data you may define for each.

Tool	note	Tool	note
	Line. Click to start, click to end.		PolyLine. Multiple line segments drawn as a whole. Click to start, click to end segment, double click to end.
	Rectangle. Click to start, click to end.		Circle. Click to start, click to end.
	Text. Define text, *angle*[26], font size. Multi line text is possible. Also can save & load 'standard' text		ISO Polish symbol. Define grade text, *angle*, Rq value [over triangle], sampling length [under bar]
	ISO Grind symbol. Define grade text, *angle*, Rq value [over triangle], sampling length [under bar]		ISO Datum symbol. Define datum label [usually A, B or C] and *angle*.
	Text – greek. Select from range of usefull greek symbols. Define *angle*.		Reference box. Select from range of symbols for first section. Define text for next two sections. Define *angle*.
	Polish symbol – pre ISO. Select grade P1, P2, P3 or P4 and angle.		Grind symbol – pre ISO. Select grade G1, G2 or G3 and angle
	Coating symbol.		Anti reflection coating.
	Coating symbol: front mirror.		Coating symbol: mirror rear
	Empty symbol circle. Same size as coating symbols.		Reference point.

For line & polyline - Press SHIFT key while moving to force vertical or horizontal line.



Undo last drawing action

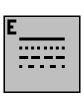


Edit user draw items on preview form

8.3.2.2 Editing

To edit user drawn items, click on the botton shown here. Tolerancer will display a dialog. At the right hand side you will see a list of the items in order [first at top]. If you select an item in the list, it will be highlited [in red] on the preview.

In this dialog, you can alter the definitions of individual drawn items. You can also delete or move [en bloc] one or more drawn items.



Line style options on preview form

8.3.2.3 Linestyles

There are a number of line style options: these apply to lines & polylines only. You may select:

1. line thickness [from 5 widths]

---

[26] *Angle* means angle of text or symbol from horizontal. Angle is measured anticlockwise in degrees.

2. line type [solid, dotted, dashed etc]
3. arrow type [none, left arrow, right arrow, both]

You may also opt to have a length value shown with the single line. This length is in the same units as the element drawing, and may be useful for showing non-standard dimensions.

8.3.3 Zoom/pan

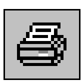
By default you may zoom in manually to the drawing, by selecting an area [click down, move mouse and release mouse]. This is complimented by the following buttons:

Button	Action
	Restore picture to filling preview
	Zoom in about center of preview
	Zoom out about center of preview
	Enable/disable panning. When panning is enabled, mouse pointer changes to a hand. To pan, click down on the drawing and move the mouse. Panning stops when you release the mouse button. While panning is enabled, you cannot zoom in manually

8.4 ISO output

There are three different types of output available from the ISO editor. There are a few subtle differences.

8.4.1 Printer

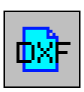


Printer button on ISO editor

The printer button will create a high resolution of the drawing which fits nicely on the page. The unzoomed preview is an exact replica of the printout, fonts and all, except at a lower resolution.

PDF files. You can output to a PDF file, **IF** you have the appropriate third party software[27].

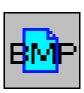
8.4.2 DXF



DXF button on ISO editor

AutoCAD compatible file for export to full CAD systems. AutoCAD fonts are quite different from Windows True Type fonts, so the output may appear somewhat different.

8.4.3 Bitmap [BMP]



Bitmap button on ISO editor

Bitmap file of current preview – so if zoomed in, this bitmap will just show that portion of the full drawing.

[27] Basically, printer drivers that allow you to print to a PDF file as if it were a printer. In tests, Adobe PDF writer had problems, but Adobe Distiller was fine. PDF995 [shareware utility] also seemed to be satisfactory.

8.5 Element drawings

The ISO 10110 element drawing created by Tolerancer, shows the full information required by an external or internal glass shop to manufacture and inspect the selected element.

The drawing follows part 10 of ISO 10110 for its layout. It consists of three main parts:

- table field [design parameters, tolerances and permissible imperfections]. This is divided into 3 sub fields [left surface, material, right surface]
- drawing field – schematic of element with all info not in the table
- title field or footer. This holds general information, such as element name, reference number, company title etc etc.

In our implementation we have added a few extra sections, such as a system outline, focal length, scale etc. These can be shown or hidden as required [see 'Preferences: section 8.2.1]

8.5.1 Surface

In lens design, a surface is defined by its radius of curvature, an aperture and, optionally, some aspheric coefficients.

This is not sufficient for manufacture. Extra detail is required in the form of tolerances and permissible imperfection levels, as defined in ISO 10110.

The ISO editor: surface table allows you to edit all necessary items. Most are perfectly clear, and will not be discussed, but a few require extra notes.

8.5.1.1 Apertures, edges & chamfers

On first inspecting the ISO editor in surface editing mode, you will see that there are three different diameters; all of which may need to be specified.

diameter name	meaning
Dia – active surface	Value of aperture diameter parameter as used in lens design program. The parameter cannot be changed, but the displayed text can be edited manually.
Dia – edge of glass	Diameter of edge of lens element. This is >= active surface diameter for both surfaces. You can edit this value – especially if you want to chamfer a surface.
Dia - effective	Diameter used for application of coating. This is only displayed in the tolerance table. It is <= active surface diameter

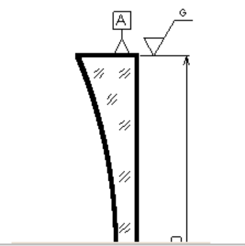
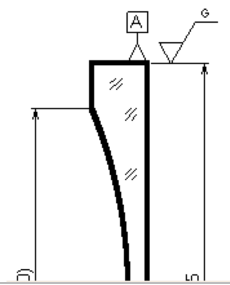
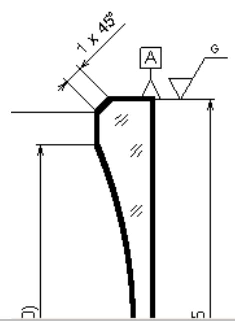
Tolerances on the edge diameter may be entered manually. However it is also possible to use the ISO standard method for diameters[28]. If this method is used [by checking 'Use ISO dia. tols' checkbox], then the drawing contains a new field displaying the meaning of the symbol.

Protective chamfers may be placed on 'corners' to prevent chips etc. These are defined simply in the table by a maximum and minimum dimension. They are not drawn.

---

[28] ISO diameter tolerances are taken from standard tables and defined by a 'position' [letter: a-h] and a grade [number: 4-11]. Thus, for a 50mm dia block, 'h4' corresponds to +0, -0.007mm, but 'a11' corresponds to -.32 to -.48mm

Larger chamfers may however be defined and drawn for concave surfaces; provided that there is sufficient 'room', i.e. the element edge diameter must be larger than the active surface diameter for that surface.

Item	value	action	drawing
Active surface Element edge dia Chamfer length	X mm X mm 0 mm	Default. Only edge dimension is shown, as active surface has same value.	
Active surface Element edge Chamfer length	X mm X+dX mm 0 mm	Expand edge diameter to allow space for chamfer. Active surface aperture dimension now appears	
Active surface Element edge Chamfer len Chamfer angle	X mm X+dX mm Y mm Z degree	Define chamfer. Note that an extra aperture dimension appears for inner dia of chamfer	

8.5.1.2 Aspherics

Some elements have one or even two aspheric surfaces. Such elements have two drawings – a standard page and another page which details in two extra tables:

- aspheric definitions
- tolerances[29] on the surface [sag & slope].

You can toggle between the two in the preview by checking the 'aspheric' check box at the bottom right of the preview form.

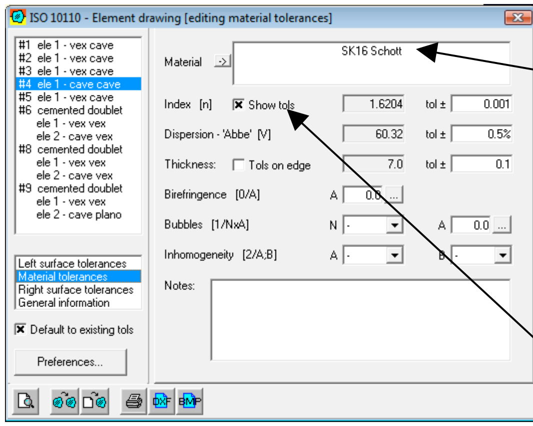
When you print or output to a DXF file output, both pages are created automatically. If you generate a bitmap, then that BMP file only contains what you see in the preview.

---

[29] These are defined in the 'aspheric' tab. You may specify sag and/or slope at a number of points across the surface radius [defined by you]. By default these are equally spaced, but each 'height' can be altered.
You may define sag and slope tolerances at the center and edge of the aperture and get the program to interpolate intermediate values. Any tolerances can be edited manually.

8.5.2 Material

There are a few points of interest on specifying materials. Look at the ISO Editor.

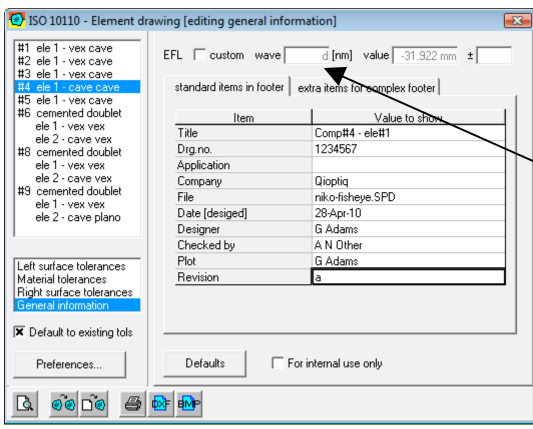


First, by default the material name is obviously that defined in the lens drawing. However, you can edit this box [maybe to show alternatives], without altering the actual design data.

Second, you may choose to show or hide the material tolerances in the material sub field of the tolerance table.

8.5.3 General

The ‘General information’ section of the ISO Editor allows you to specify and edit data for the ‘footer’ field in the drawing.



By default the focal length is calculated for the mid design wavelength.

However you may define the focal length value at a custom wavelength.

The spreadsheet provides easy access to the various fields shown in the footer.

The complex footer has more fields, and these are accessed via another spreadsheet in the second tab in this display.

Clicking the ‘defaults’ button only sets default values for the general information [it has no effect on the surface or materials tolerances]

8.6 Cemented component drawings

Cemented component drawings are different from element drawings. These are classed as 'an optical sub assembly' – ISO 10110 part 1. Being assembly drawings for two or more elements, information already upon the element drawings does not need to be replicated.
However, some extra information is displayed as per standard:

- element part numbers [parts list reference numbers]
- details of cement or other bonding methods
- dimensions & tolerances that are in addition to those given in the detail drawings
- focal length

8.6.1 Component values & tolerances

Tolerancer allows you to handle cemented doublets or triplets. You may specify a number of items for different parts of the drawing:

Component outline:

- Tolerance on thickness for component
- Element flags [part numbers] by default these are the drawing numbers defined for each element in the general section for the individual elements. However you can edit these if wished.

Parts list:

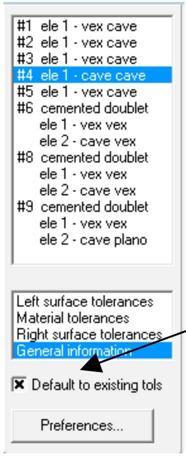
- Number of copies of each element required to make up the component [almost always =1]
- Notes for each element

Tolerance table:

- Cement for each interface
- Centering tolerance for exterior surfaces
- Centering tolerance for interface

8.6.2 General

Information for the footer. As described in section 8.5.3, for the element drawing.



8.7 Using tolerances from main program

You may enter ALL ISO drawing tolerances manually. However, some can be taken directly from the main program. Here we note which values can be taken over and where they are specified in the main program [i.e. name of appropriate column headers in the relevant tolerance editors]

To use the tolerances from the main tolerance editors, simply check the 'default' to existing tols' check box at lower left of the ISO editor.

By default, then program will then display the values shown below. However, you can edit these if desired!

The name used is that shown in the ISO Editor.

Surface:

- Radius
  'Radius' tolerance[fringes] – *symmetric tolerance editor* - converted to percent radius tolerance

- Form [3/A[B/C]
  A 'Radius' tolerance [fringes] – *symmetric tolerance editor*
  B 'Cylinder' tolerance [fringes] – *form tolerance editor*
  C 'Sag' tolerance [fringes] – *form tolerance editor*

- Centering [4/]
  'Wedge' tolerance – *asymmetric tolerance editor* – values used in ISO drawing are simply derived[30] from the wedge value

Material

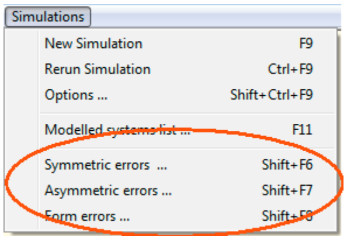
- Index [n]
  'Refractive index' tolerance – *symmetric tolerance editor*
- Dispersion – 'Abbe'
  'V-Value' tolerance – *symmetric tolerance editor*
- Thickness
  'Separation' tolerance – *symmetric tolerance editor*

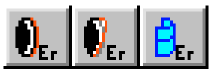
---

[30] The exact value depends upon the datum[s] selected for that element:

- Datum on edge only:
  4/ tolerance of both surfaces is 0.5 of wedge tolerance
- Datum on edge and one optical surface:
  4/ on datum optical surface = 0
  4/ on non datum surface = wedge tolerance
- Datum on two optical surfaces
  4/ on both surfaces is 0.5 of wedge tolerance

9. User defined errors





You can now insert specific errors into a system and see the impact in the various performance graphs.

Because we already have three forms [ch 6.5] which display errors of each of the main groups [symmetric, asymmetric & form – see chapter 10] for systems in a simulation, it seemed more logical to enhance these forms, so that you can also specify tolerances. Therefore, these 'editors' are accessed via the simulation menu.

At the bottom of all three of these forms, you will see a check box labelled 'User defined errors'. This checkbox toggles between the two modes:

- [***unchecked***] – displays errors of current system in simulation list [read only]
- [***checked***] allows entry/editing of user defined errors. This DOES NOT alter the errors of the systems in the simulation. These are completely separate.

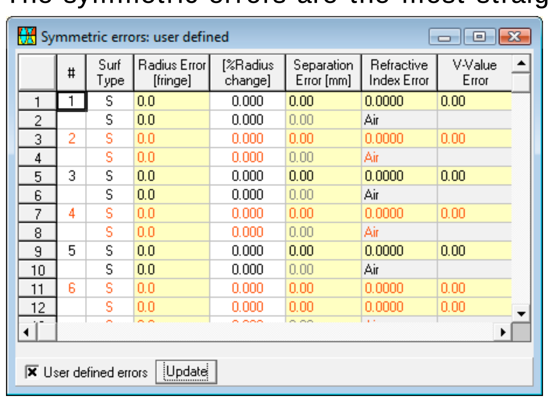
When in error editing mode, you will also see an 'update' button. The linked graphs will only be updated when you click this button – this is to allow you to enter several errors in quick sequence without having to wait for the full calculations to be carried out. On the linked graphs – the performance curves from the nominal system are also shown, but are drawn in faint grey.

When you change state, you will find that this applies automatically to all three forms.

We will now discuss these in more detail.

9.1 Symmetric user errors

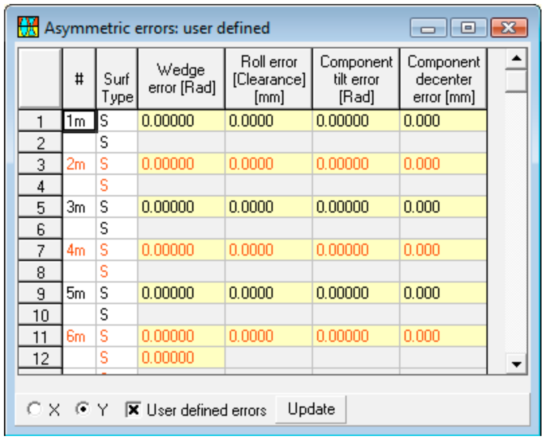
The symmetric errors are the most straight forward of the three. In it you may edit radius, separation, refractive index and V-value.



When you edit the radius, so the equivalent % radius change is also displayed in the column.

9.2 Asymmetric user errors

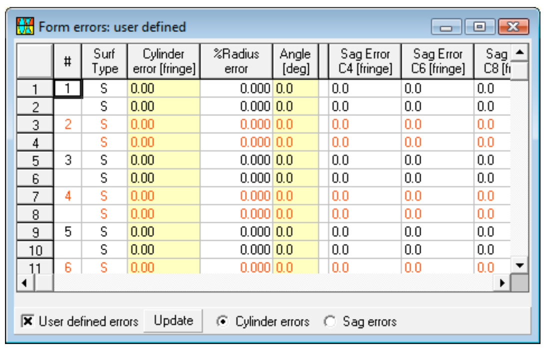
The asymmetric error editor is fairly straight forward. However, asymmetric errors are vector in nature [x & y components]. You may toggle between these two components using the option buttons at bottom left.



When you click the update button all errors [whether x or y] will be modelled.

9.3 Form user errors

As discussed in chapter 10.3, form errors fall into two categories within Tolerancer, i.e. cyllindrical error and symmetric form irregularity.



You may choose to edit/simulate one type or another at any given time, but not both. Choose by clicking the option buttons at bottom right of this form.

10. Manufacturing Errors

WinLens Tolerancer is designed to work with systems which have an axis of rotational symmetry [nominally].

For such systems manufacturing errors may be split into three great categories

- Symmetric
- Asymmetric
- Form[31]

These in turn are divided into further sub categories.

10.1 Symmetric errors

Symmetric errors do not affect the degree of symmetry of a system with an axis of rotational symmetry. This class covers both dimensional perturbations [curvature and separation] and material properties [index and V-Value].

10.2 Asymmetric errors

A single asymmetric error leaves a rotationally symmetric system with a single plane of symmetry. Included in this class of error are tilts and decenters. Such errors are vector in nature, i.e. have a specific direction, and may be resolved into x and y components.

Since optical systems are defined as a set of surfaces, the obvious errors are tilts and decenters of those single surfaces[32], and these are assessed in the sensitivity analysis.

However, these do not take into account the actual linkages between surfaces. Though optically critical, mechanically surfaces are just the boundaries of the blocks of glass. We therefore define a further set of element and component related errors, which also allow for errors in the mechanical support:

- Element wedge
- Roll [clearance]
- Component tilt
- Component decenter

These are described in the sub sections below.

10.2.1 Element wedge

This is created by the centering process, but its effect depends upon the way the component is mounted. Wedge occurs in an element, when the optical axis [line between the centers of curvature of the two surfaces] does not correspond to the mechanical axis as defined by the edge of the element.

When the element is placed in the mechanical mount, one surface placed against the mount and is therefore true. The other surface is then tilted by the amount of the wedge error. If further elements are cemented to the tilted surface, these surfaces are also tilted and decentered [even if the second element is perfect in itself]. You may be able to choose the mounting surface [see section 5.2.1], or the

[31] This includes sagitta, rotationally symmetric irregularity and asymmetric irregularity. The former equates to curvature errors

[32] Note that for a single spherical surface, a tilt, β, is related to a decenter, δ, by the simple equation $\delta = \beta.r$, where r is the radius of curvature of the surface.

mounting surface may be dictated to you by the shape of the lens as a whole.

10.2.2 Roll [clearance]

Even if the component is perfect in itself, it will probably be tilted about the mounting surface, because there must be some clearance to allow the component to be inserted into the lens barrel. The component will be able to rotate on the mounting surface until one corner touches the barrel.

The mounting surface will stay centered, but all other surfaces will be tilted and decentered. You may define tolerances for the clearance for each component. The mounting surface may also be selected [as noted in previous section]

10.2.3 Component tilt and component decenter

In most optical systems the components are of different diameters. The lens barrel must there be created by a separate series of operations [especially if the barrel has to be turned round]. Each section of the barrel may therefore be tilted and decentered with respect to the datum axis for the entire mount. In WinLens Tolerancer you may define tolerances for these errors for each component.

10.3 Form errors

Form errors are the catch all class, covering all surface shape perturbations.

Following ISO 10110 section 5, form or surface errors may be divided into:

- sagitta
- rotationally symmetric irregularity [aspheric irregularity]
- asymmetric irregularity

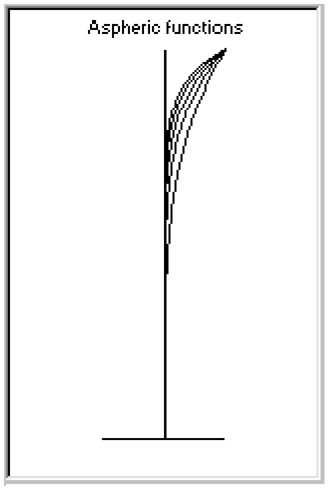
Sagitta error corresponds to curvature error which, in WinLens Tolerancer] is handled with the symmetric errors [see 10.1 above]

Rotationally symmetric irregularity is a sag error which varies with radius only. The functional form of such variation is not really known - there is certainly very little in the literature on this subject.

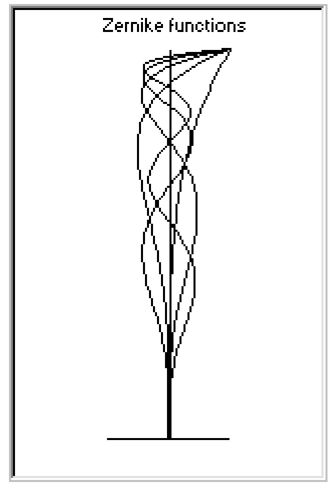
In WinLens Tolerancer, we choose to model such errors by altering the aspheric coefficients. However we do not use the standard power series terms independently. Instead we manipulate them using Zernike coefficients.

By using Zernike coefficients, we have an orthogonal set of terms, which yield zonal perturbations [lumps and ripples] more like those encountered in real life. This is illustrated below

Variations in sag from altering power series coefficients independently.



Variations in sag from altering Zernike coefficients independently.



Finally, asymmetric irregularity covers all other surface perturbations. The most obvious member of this group is cylinder error, in which a slight amount of power is added to one section of a surface, leaving it toroidal in form. WinLens Tolerancer handles cylinder errors only.

11. Optical Effects of Manufacturing Errors

Manufacturing errors [chapter 10] can effect any optical performance measure, from focal length to spot size or MTF.

Some optical effects of the errors are common to all error classes [section 11.4], while others are characteristic of a specific class.

11.1 Effects of symmetric errors

The most obvious effect of symmetric errors are changes in the paraxial properties, such as EFL and BFL.

The wavefront aberrations produced by rotationally symmetric systems may be described by the standard 3rd [Seidel], 5th, 7th order polynomials. It seems that the higher order terms are fairly stationary under perturbation, compared to the Seidel aberrations. Therefore in WinLens Tolerancer the higher order terms are ignored.

11.2 Effects of asymmetric errors

The introduction of a small tilt or decenter introduces even order terms to the wavefront polynomial. Of these, the predominant aberrations are:

- bore sight error
- tilt of the axial ray in image space
- axial or field constant coma
- linear astigmatism [tilt of the T and S fields]

In WinLens Tolerancer you may see these collectively referred to as Asym. Abns or 0th/2nd order Abns.

11.3 Effects of form errors

The most characteristic effect of cylinder errors is axial astigmatism, i.e. astigmatism occurring on the optical axis.

Asphericity errors [rotationally symmetric irregularity] may be thought of as ripples on the surface. Low order aberration theory is not appropriate to probe the effects of such errors. Instead WinLens Tolerancer uses standard ray fans [in the meridian and sagittal planes] traced at several field positions. From the ray fans, we obtain several quantities which describe the changes in transverse ray aberration [TRA] and optical path difference [OPD] across the fans. These ‘aberrations’ are:

- Mean TRA [averaged over both section]
- Peak-Valley TRA [found over both sections]
- Peak-Valley TRA in meridian section
- Peak-Valley TRA in sagittal section
- Mean OPD [averaged over both section]
- Peak-Valley OPD [found over both sections]
- Peak-Valley OPD in meridian section
- Peak-Valley OPD in sagittal section

Some aberrations may be more appropriate than others. Since the TRA is obtained by differentiating the wavefront aberrations, TRA make a useful probe of the slope in wavefront.

11.4 Effects common to all error classes

All classes of error may effect the chief ray aberrations [astigmatism, distortion], spot sizes and MTF.

As explained in section 4.1, chief ray aberrations tend to be linear functions of the manufacturing errors and may therefore be specified in the performance requirements.

We have noted that for symmetric and asymmetric errors, the T field astigmatism[33] tends to change more rapidly than the S Field. If you look at the sensitivity analysis [either the numerical display or the field aberration plots] this is quite clear.

Spot diagrams provide a nice visual understanding of the impact of manufacturing errors, whilst MTF is often used as the final arbiter in judging a system. Both performance measures combine the changes in all aberrations and are therefore effected by all classes of error.

[33] In symmetric errors, this is of course T/S field curvature, whilst for asymmetric errors this constitutes T/S field tilt.

12. Hints & Tips

A few extra notes which may be of assistance.

12.1 Preparation of the WinLens Files.

You cannot alter the nominal design in WinLens Tolerancer. Therefore you must ensure that the lens file [.SPD] is correct.

Area of concern	Action
Defocus	Make sure this is the correct value, as you cannot change it in WinLens Tolerancer.
MTF Scales	In the sensitivity tables, we show the MTF values at 1/3, 2/3 and 3/3 of the max transverse MTF frequency. Since this scale[34] cannot be changed in WinLens Tolerancer, make sure it is ok first.
Zooms	During loading, sensitivity analysis and simulations all zooms are analysed. Therefore if you have a system with many zooms, and you only need to analyse a few zooms, make a copy of the original file and then remove the unneeded zooms in WinLens.

12.2 Tolerance awareness

While tolerancing should not be left to the mechanical designers or glass shop workers, neither should they be ignored. They need to be involved in discussion about mounting techniques, and they will have information about tolerance costs and knowledge of what is possible in your shop.

12.3 Choosing performance specifications

This is a key activity in Tolerancer. There is a wizard available to help you, plus more notes in section 3.1 of this manual

[34] Many other scales can be changed as they would not require major recalculations. Changing the MTF scale would require major recalculations for nominal system, sensitivity and any simulation results. It is therefore prohibited.

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