TOR-Wavefront Differential Tolerancing
(MTF, RMS Wavefront Error, Fiber Coupling Efficiency, Polarization Dependent Loss)

The Wavefront Differential Tolerancing (TOR) option is based on a wavefront differential algorithm and calculates changes in RMS wavefront error, MTF, fiber coupling efficiency (CEF), or polarization dependent loss (PDL) due to changes in the constructional parameters of any lens system definable in CODE V. Compensating parameters may be used to simulate the manufacturing and assembly process, and automatic budgeting may be done. Tolerances may be changed interactively to alter the budget and see its effects. Tolerances become part of the lens data, and can be used by TOR, Distortion Tolerancing (TOD), Primary Aberration Based Tolerancing (TOL), or the user tolerancing macros (TOLFDIF and TOLMONTE). For details about using TOLFDIF and TOLMONTE, see “User-Defined Tolerancing” on page 20-107.

When to Use the Wavefront Differential Tolerancing (TOR) Option

Optical designers are responsible for ensuring the quality of images for systems that they design, and usually are responsible for ensuring that the design is buildable. Since tolerances will generally degrade the overall performance (carefully obtained through optimization and balancing of contending requirements), it is important for the designer to ensure that the performance will be maintained in the fabricated units or that a reasonable yield of satisfactory units will be obtained. So, sometime during the design process, tolerances are needed; often this is done early in the design cycle to help choose configurations that are not unduly sensitive to errors, or to provide guidance on how to desensitize the design. Tolerances of the finished design are needed in order to have the units properly built.

TOR, through its easy generation of the default run initial tolerance budget, and its fast calculation using wavefront differentials, can be used to quickly identify the driving parameters. Further refinement of runs can be made to modify this first-cut budget by trying different tolerances, assembly procedures (through compensation schemes) and shop limits that may be more appropriate to the fabrication group who will build the system. If, for any reason, the system seems to be “impossible” to build, consider including the ALI (Alignment) option (Chapter 21) as a part of the assembly process, which can compensate for unknown and unmeasured manufacturing errors by using interferograms of the assembled unit and the data for the nominal design to predict both the adjustments to make and the improvement to be obtained.

TOR, TOD (chief ray distortion tolerancing) and ALI are related wavefront differential tolerancing and adjustment programs, and use wavefront differentials and tolerances in a manner consistent with each other; TOL, using a subset of the available tolerances, is a first- and third-order tolerance analysis program with Monte Carlo features that may help to cover some special needs.

TOR includes:

- The effect of all LDM tolerances
- Optional compensators to simulate the effect of assembly adjustments
- Optional constraints to keep boresight corrected at one image point
- Vignetting, apertures and obscurations matching the as-built system
- Polychromatic effects, if desired
- Gaussian and user-defined apodization
- Decentered systems
- Unusual surfaces and features (HOEs, non-sequential surfaces, interferometric deformations, GRIN, etc.) - if it can be traced, it can be toleranced (only polarization effects are omitted)

For details about defining tolerances in the LDM, see “Defining Tolerances” on page 8-3.

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Default Operation

From the command line, the Wavefront Differential Tolerancing (TOR) option calculates the value of each tolerance which will give a degradation of 0.01 in RMS wavefront error (for that tolerance) at the worst field/zoom position with the restriction that the tolerance is rounded to one or two significant figures and that the tolerance lies between upper and lower bounds. If any tolerances have been entered in the LDM, TOR assumes that all needed tolerances and compensators have been defined, and uses them. If no tolerances were defined in the LDM, a default set is generated; if, in addition, no compensators were defined, defocus is supplied as the compensator (CMP DLZ SI). The default set of tolerances are those which are most often needed for a centered system (equivalent to the LDM command DEF TOL SA). TOR uses Gaussian apodization and/or user-defined apodization if present in the lens data.

For details about defining tolerances in the LDM, see “Defining Tolerances” on page 8-3.

Command Mnemonics
(alphabetical)

AZI	BAR	BGI	BGP	BOR	CDT
CNS	COM	DB	DEP	DST	ERF
FRE	FUL	GRI	INN	INV	LIM
MPR	NEG	NRD	PDD	PDI	PDS
PER	PHN	PLO	RNA	RNX	RNY
ROU	SCN	SEL	SNS	SRC	SYM
TGR	WBF	WTC	WTD	WTF	WTS
XYZ					

Defining Performance Measures

With the Wavefront Differential Tolerancing option, you can calculate changes in RMS wavefront error, MTF, fiber coupling efficiency (CEF), or polarization dependent loss (PDL) due to changes in the constructional parameters of any lens system definable in CODE V.

- To use RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays, with the **Performance Measures** tab automatically displayed, and the **Polychromatic RMS** button selected.
- To use MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays, with the **Performance Measures** tab automatically displayed, and the **Polychromatic MTF** button selected.
- To use CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. The **Tolerancing - CEF** dialog box displays, with the **Performance Measures** tab automatically displayed, and the **Fiber Coupling Efficiency** button selected.
- To use PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. The **Tolerancing - PDL** dialog box displays, with the **Performance Measures** tab automatically displayed, and the **Polarization Dependent Loss** button selected.

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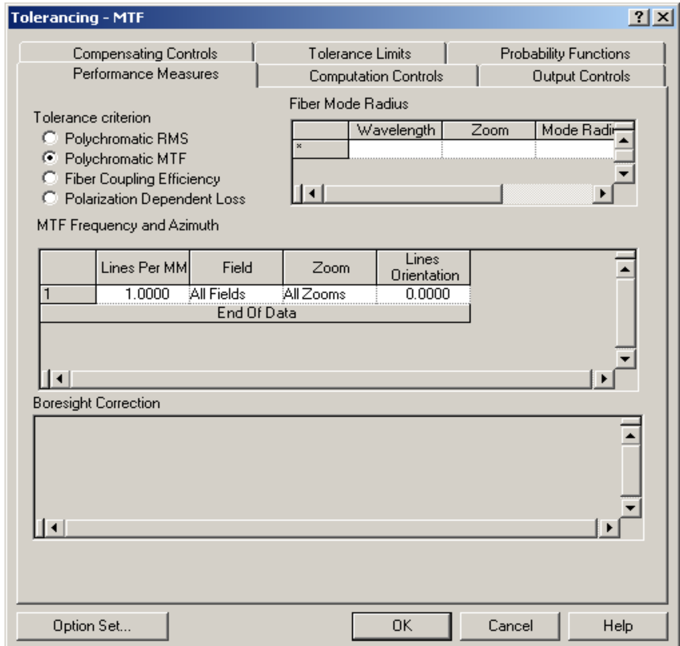
Define the performance measure controls as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
GUI command only.		
Tolerance criterion: **Polychromatic RMS** **Polychromatic MTF** **Fiber Coupling Efficiency** **Polarization Dependent Loss**	Specifies whether you want to use RMS, MTF, fiber coupling efficiency (CEF), or polarization dependent loss (PDL) tolerancing. **Note:** The MTF and CEF calculations assume a polarized input beam when polarization ray tracing is enabled (POL Y, or **Activate Polarization Ray Tracing** in the **System Data** window). The PDL calculation always assumes a polarized input beam.	Determined by **Analysis > Tolerancing** menu choice.
FRE lines_per_mm | No....f,z		
Spatial frequency	If you choose the **Polychromatic MTF** button, the **Spatial frequency** spreadsheet is activated. Specifies spatial frequency for MTF tolerancing (line pairs/mm). **Range**: 0 to cutoff.	1 line per mm.
AZI TAN | RAD | line_orientation_degr....f,z		
Azimuth (degrees)	Specifies orientation of spatial frequency (degrees). RAD: 0° TAN: 90°. Use only with FRE (MTF tolerancing). **Range**: 0 to 180.	90.0 (Tangential target).

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Command Syntax

Screen Control	Explanation	Default
MPR [PDL] mode_radius....z,w		
Tolerance criterion: Fiber Coupling Efficiency/Polarization Dependent Loss/ Fiber Mode Radius	Activates CEF tolerancing and specifies the output fiber mode radius (in lens units). In the GUI, you must select the **Fiber Coupling Efficiency** or **Polarization Dependent Loss** button to activate this spreadsheet. The MPR command operates under the following conditions: – The output fiber mode is assumed to be Gaussian. – The input fiber mode is simulated by Gaussian pupil apodization, defined by PUI, PUX, and PUY. A uniform pupil may be used, but this is typically not appropriate for fiber systems. Apodization defined by INT files is not recognized. – The output fiber is located at the image surface vertex and oriented along the Z-axis. To reposition or reorient the nominal output fiber, use the FLO command in the LDM (**Lens** > **System Data** menu, **Output Fiber** page in **System Data** window). – Weights specified in TOR (WTF and WTW commands) are used for relative weighting of the different zooms, fields, and wavelengths. If multiple wavelengths are used, the output gives the weighted average of coupling efficiency over wavelength.	Command line: none. GUI: 0.0052 (SMF-28 fiber at 1550 nm with system units of mm).
BOR [Fi] [Zk] [XC | YC] [L'label'(3)] Yes | No		
Boresight correction	Specifies boresight correction. In addition to any other compensation, constrains change in image position at field Fi, zoom position Zk, to zero, using all compensators. Defaults: F1, Z1. XC – Correct X component only YC – Correct Y component only neither – Correct both X and Y components Label ('label'), if present, uses only the compensators of that labeled group. Only one image point (Fi, Zk) permitted per labeled group; reuse of the label on a second command will replace the first. If no appropriate compensators are provided in the LDM, BOR will fail to operate. Change in image position determined by: MTF – Chief ray RMS – Average deviation of entire bundle	No.

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Command Syntax		
Screen Control	**Explanation**	**Default**
CNS DX | DY | DZ [Fk | Fi..j] [Zk | Zi..j] [Tk | Ti..j] max_absolute_shift		
Command line only	For RMS tolerancing only. Lagrange multiplier constraint on tolerances. Constrains the X, Y, and Z shifts of the center of the best fit reference sphere so that their absolute values are no greater than the specified max_absolute_shift. Specify: DX – Constrain X shift DY – Constrain Y shift DZ – Constrain Z shift For each tolerance, the X, Y, and Z shifts are computed assuming optimal compensation. Constrains reference sphere shifts at a given range of fields (Fk | Fi..j), zoom positions (Zk | Zi..j), and/or for a given set of tolerances (Tk | Ti..j). Defaults: F1, Z1, and T1.	No.
WTC DX | DY | DZ [Fk | Fi..j] [Zk | Zi..j] [Tk | Ti..j] weight		
Command line only	For RMS tolerancing only. Weighted constraint on tolerances. When the weight is non-zero, the X, Y, and Z shifts of the center of the best fit reference sphere are considered in the compensation calculation. The larger the weight, the lower the absolute magnitude of the shift will be, at the expense of less optimal compensation that results in greater RMS wavefront error. Specify: DX – Constrain X shift DY – Constrain Y shift DZ – Constrain Z shift For each tolerance, the X, Y, and Z shifts are computed assuming optimal compensation. Constrains reference sphere shifts at a given range of fields (Fk | Fi..j), zoom positions (Zk | Zi..j), and/or for a given set of tolerances (Tk | Ti..j). Defaults: F1, Z1, and T1.	No.

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Defining Zernike Polynomial Controls

You can define multiple error functions for TOR based on Zernike polynomials and use those to determine tolerances. The Zernike polynomial controls are only available on the command line.

See "Zernike error functions in TOR" on page 20-57 for an example of how to use this feature.

Command Syntax		
Screen Control	**Explanation**	**Default**
ZRN [ENP | EXP | EXS] [TIL] num_terms or **ZFR** [ENP | EXP | EXS] [TIL] num_terms or **ZFE** [ENP | EXP | EXS] [TIL] num_terms		
Command line only	Fit the entrance pupil (ENP), exit pupil (EXP), or exit sphere (EXS) for each field and wavelength to a Zernike polynomial. If the ENP, EXP, or EXS keyword is omitted, EXS is used by default. ZRN specifies standard Zernikes; ZFR specifies fringe Zernikes (37 terms); ZFE specifies extended fringe Zernikes. An extended fringe Zernike may have any number of terms and only applies to circular, unobstructed pupils; the first 36 terms are the same as the fringe Zernikes. The optional keyword TIL specifies that the tilt terms in the Zernike representation of the wavefront are included in the error function. See "TOR Considerations for Microlithographic Systems" on page 20-70 for details. The ZRN, ZFR, and ZFE commands will also specify that the error function is a combination of Zernike polynomial coefficients.	No fit done.
ERF Ej erf_name [erf_weight]		
Command line only	Specifies an error function that is the weighted sum of squares of the specified Zernike coefficients and/or distortion. You can enter multiple error functions that are distinguished by the Ej qualifier. erf_name is a quoted string of up to 60 characters that is used to identify each error function. erf_weight is a weight, with a default of 1.0, that is used to combine error functions to calculate compensators. If Zernikes have been specified and no ERF command is entered, there will be a single error function whose coefficients will result in the RMS wavefront error.	Single error function whose coefficients result in the RMS wavefront error.

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Command Syntax		
Screen Control	**Explanation**	**Default**
COM Ej Ck [component_weight]		
Command line only	Defines the specified coefficient number as being a component of the Ej error function. Any number of these may be entered for a given Ej. The optional component_weight qualifier is used in the weighted sum of squares. If omitted, the standard Zernike polynomial weight that results in the RMS wavefront error will be used. Note that C1 will never be used, even if specified, since it is a constant phase term and is not used in the RMS wavefront error calculation. If no COM commands are entered for a previously defined ERF, all of the coefficients defined by the ZRN/ZFR/ZFE input will be used.	All of the coefficients defined by the ZRN/ZFR/ZFE input will be used.
COM Ej DIX | DIY [component_weight]		
Command line only	Specifies distortion in the error function. The (x,y) distortion values are determined from the (c2,c3) coefficients. The units of distortion are determined by the UNI input. The default weight is 1.0.	No.
UNI LNS | MIC | MIL | AMI | ASE | MLR | MCR | NM | IN | MM | CM		
Distortion Units (Output Controls tab)	Specifies the units of the error function if it has linear units (e.g., critical dimension), as well as the units of distortion in the distortion summary (DST) and in the merit function using DIX and DIY. LNS – Lens units MIC – Microns MIL – Mils AMI – Arc minutes ASE – Arc seconds MLR – Milliradians MCR – Microradians NM – Nanometers IN – Inches MM – Millimeters CM – Centimeters Note that IN, MM, or CM will put the distortion in those units regardless of the lens units.	Lens units (LNS)
LIS [SEN] [PER] num_terms		
Command line only	Lists components of Zernikes in sensitivity (SEN) and performance (PER) tables. Num_terms indicates how many terms to list. If num_terms is zero or omitted, all terms are listed.	No.

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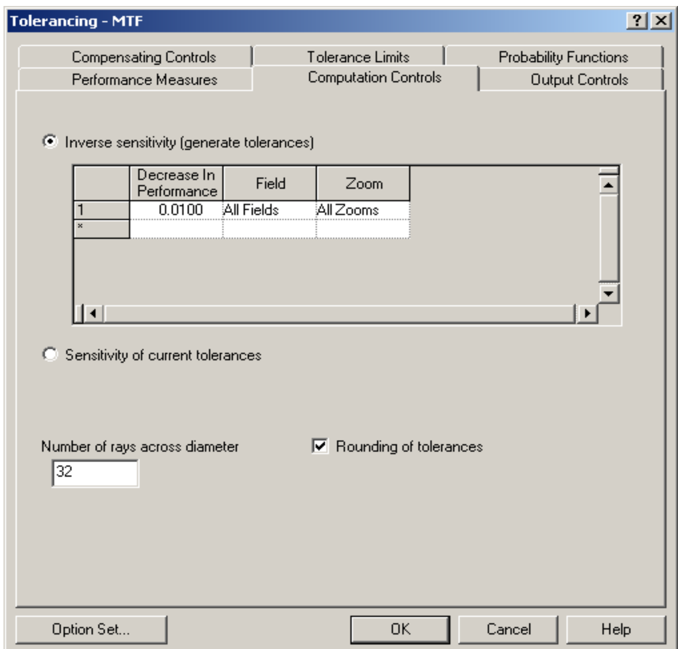
Defining Computation Controls

To define computation controls for the Wavefront Differential Tolerancing option:

- If you are using RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays. Click the **Computation Controls** tab.
- If you are using MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays. Click the **Computation Controls** tab.
- If you are using CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. The **Tolerancing - CEF** dialog box displays. Click the **Computation Controls** tab.
- If you are using PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. The **Tolerancing - PDL** dialog box displays. Click the **Computation Controls** tab.

Define the computation controls as described in the following table.



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Command Syntax		
Screen Control	**Explanation**	**Default**
INV [DCP] [decrease_in_performance....f,z]		
Inverse sensitivity (generate tolerances)	Generates tolerance values; enter allowable decrease in performance measure, fields, and zooms or use displayed defaults. Use INV or SNS, not both. DCP decouples the values of two-component tolerances.	+0.01 in RMS -0.01 in MTF or CEF (Note: This value is always computed in terms of coupling efficiency (CEF), and is displayed in dB if DB Yes is used.)
SNS		
Sensitivity of current tolerances	Computes sensitivity of current tolerances. Use INV or SNS, not both.	INV - Inverse mode.
NRD num_rays_across_diameter		
Number of rays across diameter	Specifies approximate number of rays traced across the pupil diameter.	32
ROU Yes | No		
Rounding of tolerances	Tolerances generated by INV will be rounded to reasonable numeric values.	Yes. Tolerances will be rounded.

Defining Output Controls

To define output controls for the Wavefront Differential Tolerancing option:

- If you are using RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays. Click the **Output Controls** tab.
- If you are using MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays. Click the **Output Controls** tab.
- If you are using CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. The **Tolerancing - CEF** dialog box displays. Click the **Output Controls** tab.
- If you are using PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. The **Tolerancing - PDL** dialog box displays. Click the **Output Controls** tab.

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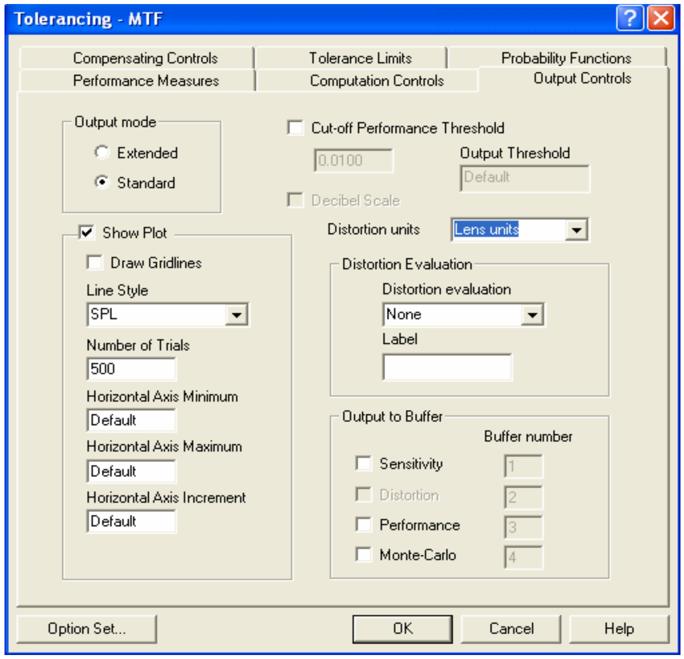
Define the output controls as described in the following table.



<table>
<tr><th colspan="3">Command Syntax</th></tr>
<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">FUL Yes | No</td></tr>
<tr><td>Output mode</td><td>Extended output mode (FUL Yes) lists: tolerance descriptions/definitions in the header, and formula coefficients describing the performance change as a function of tolerance size, in addition to standard output.</td><td>No, for 3 or less compensators.
Yes, if 4 or more compensators</td></tr>
<tr><td colspan="3">SEL [Yes | No | performance_threshold]</td></tr>
<tr><td>Cut-off performance threshold</td><td>Displays only those tolerances that introduce a change in MTF, RMS, or CEF of more than the specified performance threshold - the drivers.
Yes Selects only outputs that are:
For INV, above decrease in performance value;
For SNS, degradation worse than 0.01
No Lists all tolerance effects
performance_threshold
Selects only outputs that exceed specified value</td><td>No.</td></tr>
</table>

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Command Syntax		
Screen Control	**Explanation**	**Default**
PLO [GRD | GRX | GRY] [SPL | LIN | PNT] [#_trials [min_errf [max_errf [delta_errf]]]] or **PLO** No		
Show Plot	Produces plotted output showing the cumulative probability of the image quality versus the figure of merit, which is either RMS wavefront error, MTF, or coupling efficiency. Each zoom position is plotted separately, with up to 11 fields on a single plot. If there are more than 11 fields, there will be multiple plots for each zoom position. Is generated automatically when you run TOR from the command line. You can disable the plot using the GRA No command. Select **Show Grid Lines** (GRD qualifier) to draw grid lines in X and Y on the TOR plot. Otherwise, only axis ticks are drawn. From the command line, you can specify whether grid lines are drawn in the X and Y axes using the GRX or GRY qualifiers. Other available qualifiers are: **Line Style**. Choose from spline fit on data (SPL), connect points with straight lines (LIN), or plot points only (PNT). **Number of Trials**. Specify the number of Monte Carlo trials (#_trials). The default value is 500. This value must be a positive integer. **Horizontal Axis Minimum**. Specify the minimum value for the X axis range (min_errf). The default is 0.0. **Horizontal Axis Maximum**. Specify the maximum value for the X axis range (max_errf). The default is 0.0. **Horizontal Axis Increment**. Increment for tick marks or grid lines on the X axis (delta_errf). The default is a range based on data with 5 axis ticks. De-selecting the **Show Plot** checkbox (PLO No) suppresses the plot output.	PLO (Show Plot)
DB Yes | No [threshold]		
Decibel Scale	For CEF and PDL tolerancing only (see MPR command in "Defining Performance Measures" on page 20-6). Convert coupling efficiency /PDL to units of decibels subject to the threshold value (**Output Threshold** field). The default threshold is -50 decibels.	No.
DST [L'label'(3)] Yes | No | ALL		
Distortion evaluation **Label**	Lists x and y distortion summary. In the GUI, you can select **None** (DST No), **Summary** (DST Yes), or **Full Listing** (DST ALL). If Full Listing is selected, contributions from each tolerance are listed as well as the summary. If a label is entered, compensators with that label are used to calibrate the distortion; label must be nonblank if used.	None, unless boresight compensators have been requested.

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Command Syntax		
Screen Control	**Explanation**	**Default**
WBF Bk | No SEN | DST | PER | ZRN | MC [APP]		
Output to Buffer/ Buffer number	Writes the TOR output to the specified buffer (except B0). No is used on the command line only, to turn off a previously entered WBF command. You can select the following types of output: **Sensitivity** (WBF SEN) Writes the TOR sensitivity tables, including sensitivity coefficients. **Distortion** (WBF DST) Writes the TOR distortion tables, including contributions from each tolerance, as well as the summary list of X and Y distortions. In the GUI, this checkbox is not available unless you select either **Summary** or **Full Listing** in the **Distortion Evaluation** field; on the command line, the buffer will be empty unless you first specify DST. WBF DST without the other qualifiers includes the full distortion data listing. **Performance** (WBF PER) Writes the TOR performance summary data, including the RMS, MTF, CEF, or PDL for each field. **WBF ZRN** (command line only) Writes Zernike sensitivity data of the compensators, if the Zernike error function has been specified. See "Defining Zernike Polynomial Controls" on page 20-10 for details. **Monte-Carlo** (WBF MC) Writes Monte-Carlo data to the buffer, whether plotted output is produced or not. For more details about WBF MC, see "Output Controls" on page 20-33. You can write all these types of TOR data to the same buffer. **Note:** The buffer will be cleared before new data is saved to it, unless it is the same buffer used in the current TOR run, or the APP qualifier has been entered. APP is only available on the command line.	Not done.
XYZ Yes | No | All		
Command line only	For RMS tolerancing only. Computes the X, Y, and Z shifts of the center of the optimally compensated, best fit reference sphere for each tolerance in the lens system and adds a table of the shifts to the TOR output. If **Yes** is entered, a table is listed that summarizes values for the probable changes in the X, Y, and Z shifts of the best fit reference sphere for each field and zoom position. If **All** is entered, shifts are listed for each tolerance, in addition to the summary table.	No.

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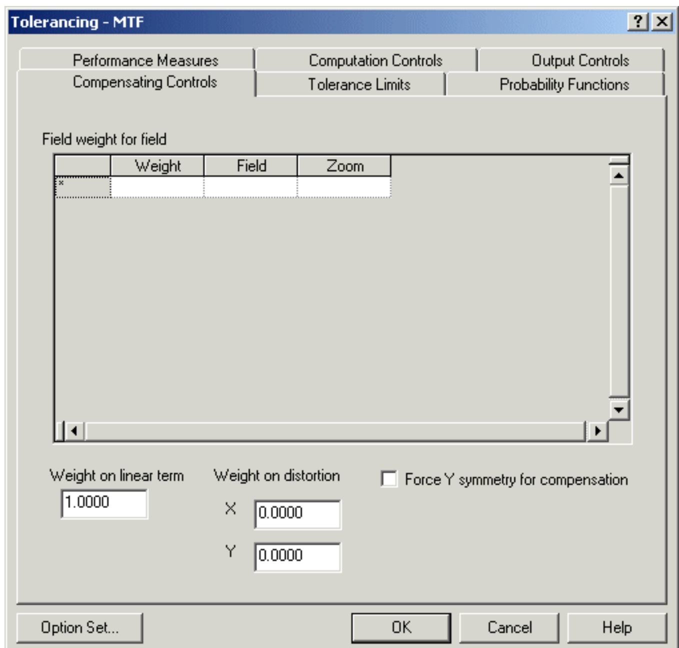
Defining Compensation Controls

To define compensation controls for the Wavefront Differential Tolerancing option:

- If you are using RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays. Click the **Compensating Controls** tab.
- If you are using MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays. Click the **Compensating Controls** tab.
- If you are using CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. The **Tolerancing - CEF** dialog box displays. Click the **Compensating Controls** tab.
- If you are using PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. Click the **Compensating Controls** tab. The **Tolerancing - PDL** dialog box displays.

Define the compensation controls as described in the following table.



Command Syntax		
Screen Control	**Explanation**	**Default**
WTF field-zoom_weight....f,z		
Field weight for field	Specifies relative weights for each field/zoom for compensation calculation. If field-zoom_weight is zero, that field will be omitted from calculation and output.	Lens system weights from WTF in the LDM.
WTS linear-quadratic_ratio		
Weight on linear term	Specifies relative weight that applies to linear term (vs. quadratic term) for compensation calculation. **Range**: 0 to infinity.	1.0 (approximately equal weight).

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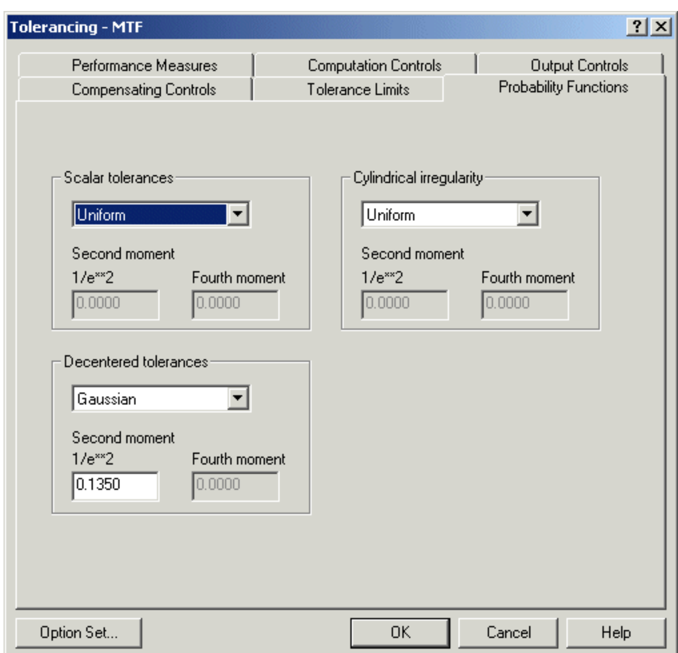
Command Syntax		
Screen Control	**Explanation**	**Default**
WTD dist_wt_y [dist_wt_x]		
Weight on distortion: **X** **Y**	Specifies weight on distortion compensation. When the weight is non-zero, distortion is considered in the compensation calculation. The larger the weight, the more emphasis is placed on distortion compensation at the expense of MTF, RMS or CEF. If dist_wt_x is omitted, it is set equal to dist_wt_y.	0.0 0.0
SYM Yes | No		
Symmetry override	Select to define the system to have rotational symmetry (regardless of actual symmetry). Used for compensation calculation.	No. Symmetry condition is defined by lens.

Defining Probability Density Functions

To define probability density functions for the Wavefront Differential Tolerancing option:

- If you are using RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays. Click the **Probability Functions** tab.
- If you are using MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays. Click the **Probability Functions** tab.
- If you are using CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. **The Tolerancing - CEF** dialog box displays. Click the **Probability Functions** tab.
- If you are using PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. The **Tolerancing - PDL** dialog box displays. Click the **Probability Functions** tab.

Define the probability density functions as described in the following table.



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Command Syntax		
Screen Control	**Explanation**	**Default**
PDS UNI or **PDS** GAU gaussian_truncation_value or **PDS** END or **PDS** MOM second_moment fourth_moment		
Scalar tolerances	Specifies probability density function for scalar (1D) tolerances. The first three forms of the command specifies a predefined density function form: UNI Uniform in 1D GAU 1D Gaussian with specified truncation value END Tolerances can only take on values at the end points, i.e., ± tolerance value The fourth form of the command allows specification of the density function by its second and fourth moments. Moments are entered for a tolerance value of 1.0 and are scaled in TOR to the actual tolerance value.	UNI.
PDD UNI or **PDD** GAU gaussian_truncation_value or **PDD** END or **PDD** MOM second_moment fourth_moment		
Decentered tolerances	Specifies probability density function for decentered (2D) tolerances. The first three forms of the command specifies a predefined density function form: UNI Uniform in 2D GAU 2D Gaussian with specified truncation value (The default value of 0.135 is the value of the Gaussian probability density function at a tolerance value that differs from the mean tolerance value by 2σ.) END Tolerances can only take on values at the end points, i.e., ± tolerance value The fourth form of the command allows specification of the density function by its second and fourth moments. Moments are entered for a tolerance value of 1.0 and are scaled in TOR to the actual tolerance value.	GAU 0.135

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Command Syntax		
Screen Control	**Explanation**	**Default**
PDI UNI or **PDI** GAU gaussian_truncation_value or **PDI** END or **PDI** MOM second_moment fourth_moment		
Cylindrical irregularity	Specifies probability density function for cylindrical irregularity tolerances. The first three forms of the command specifies a predefined density function form: UNI Uniform in 2D GAU 2D Gaussian with specified truncation value END Tolerances can only take on values at the end points, i.e., ± tolerance value The fourth form of the command allows specification of the density function by its second and fourth moments. Moments are entered for a tolerance value of 1.0 and are scaled in TOR to the actual tolerance value.	UNI.

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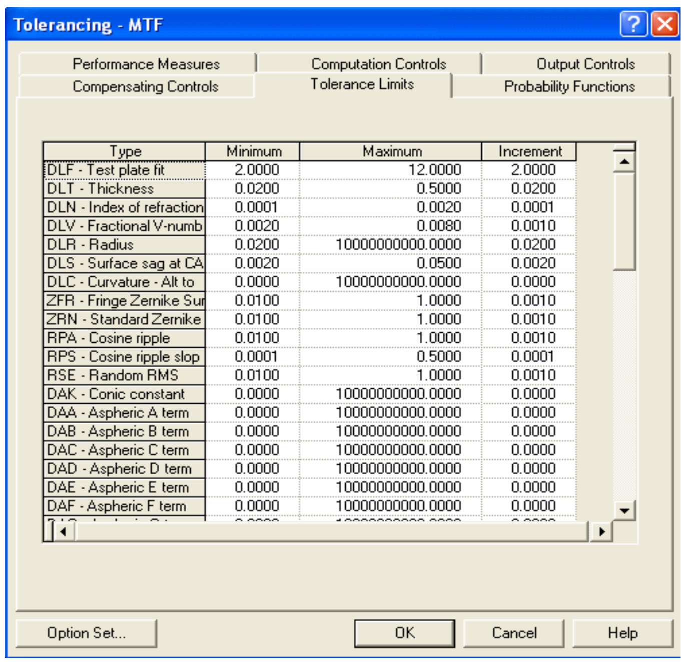
Defining Tolerance Limits

To define tolerance limits for the Wavefront Differential Tolerancing option:

- If you are using RMS tolerancing, choose the **Analysis** > **Tolerancing** > **RMS wavefront error** menu. The **Tolerancing - RMS** dialog box displays. Click the **Tolerance Limits** tab.
- If you are using MTF tolerancing, choose the **Analysis** > **Tolerancing** > **MTF** menu. The **Tolerancing - MTF** dialog box displays. Click the **Tolerance Limits** tab.
- If you are using CEF tolerancing, choose the **Analysis** > **Tolerancing** > **Fiber Coupling Efficiency** menu. The **Tolerancing - CEF** dialog box displays. Click the **Tolerance Limits** tab.
- If you are using PDL tolerancing, choose the **Analysis** > **Tolerancing** > **Polarization Dependent Loss** menu. The **Tolerancing - PDL** dialog box displays. Click the **Tolerance Limits** tab.

Define the tolerance limits as described in the following table.



Command Syntax		
Screen Control	**Explanation**	**Default**
LIM tolerance_code min max increment		
Tolerance limits	For use with INV. Allows minimum, maximum and increment for each type of tolerance to be changed. Tolerance_code is 3-letter mnemonic for tolerance.	Default limits will be used. See Table 1.

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Table 1. Tolerance Limits

LIM tolerance_code min max increment - For INV.
Defaults (where 3 numbers appear, they correspond to inches, centimeters, millimeters):

tolerance_code	min	max	increment
Centered Tolerances			
LIM DLF	2.0	12.0	2.0
LIM DLT	.001/.002/.02	.025/.05/.5	.001/.002/.02
LIM DLN	.0001	.002	.0001
LIM DLV	.002	.008	.001
LIM DLR	.001/.002/.02	1.E10	.001/.002/.02
LIM DLS	.0001/.0002/.002	.002/.005/.05	.0001/.0002/.002
LIM DLC|DAK|DAA|DAB| DAC|DAD|DAE|DAF| DAG|DAH|DAJ	1.E-10	1.E10	1.E-6
LIM HOM	5.E-6	.001	5.E-6
LIM AXG|RAG	.0001	.002	.0001
Irregularity Tolerances			
LIM IRR|CYD|CYN	.5	3.0	.5
Single Surface Decenters & Displacements			
LIM DEC|DLX|DLY|DLZ	.001/.002/.02	.025/.05/.5	.001/.002/.02
LIM TIL|DLA|DLB|DLG	.0003	.005	.0005
LIM TIR|TRX|TRY	.0001/.0002/.002	.005/.01/.1	.0001/.0002/.002
Group Decentering Tolerances			
LIM STI|STX|STY	.0003	.005	.0005
LIM BTI|BTX|BTY	.0003	.005	.0005
LIM BRL	.0003	.005	.0005
LIM DIS|DSX|DSY|DSZ	.001/.002/.02	.025/.05/.5	.001/.002/.02
LIM ROL|RLX|RLY	.001/.002/.02	.025/.05/.5	.001/.002/.02
LIM DOL	.001/.002/.02	.025/.05/.5	.001/.002/.02
Polarization Tolerances			
LIM PPA	.001	.1	.005
LIM PPR	.001	.05	.001
LIM PPO	.0003	.005	.0005
LIM PPF	.0003	.005	.0005
LIM BMN	.000001	.001	.000005
LIM BMA|BMB|BMG	.001	.05	.005
General Surface Deformation Tolerances			
LIM ZRN	0.01	1.0	0.001
LIM ZFR	0.01	1.0	0.001
RPA	0.01	1.0	0.001
RPS	0.0001	0.05	0.0001
RSE	0.01	1.0	.001

Note that test plate fit tolerances (DLF) and irregularity tolerances (IRR, CYD, or CYN) will vary within their limits, but the DLF tolerance will be maintained at a value between 2x to 4x the IRR tolerance on the same surface. If limits have been specified for both radius tolerances (DLR) and sag (DLS) or curvature (DLC) tolerances, TOR will use the limits on radius tolerances for both radius tolerances and sag or curvature tolerances.

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Linewidth Computation Controls for 1D Partial Coherence Tolerancing

The following commands comprise computations intended to meet the demand for yet smaller and smaller microlithographic features. The computations are based on the critical dimension (CD) of the image, given a one-dimensional, partially coherent image. Note that these commands can only be entered on the command line or used in a sequence file.

Some examples of the use of these computations include:

- learning how small errors in lens parameters affect the CD variation across the chip
- assessing compensation schemes given a specified tolerance
- understanding how a full polarization analysis affects process window computations.

One benefit of these capabilities is that lens manufacturers can assess their as-designed lens in terms of their customers' CD specs.

Command Syntax		
	Explanation	**Default**
CDT threshold....z		
Command line only	Computes the width of the image (Critical Dimension, or CD) of one bar of a bar object at a given intensity threshold. For a multi-bar object, the central bar is used for an odd number of bars and the left-of-center bar for an even number of bars. (Bar orientation is specified with the AZI command.)	
BAR num_of_bars width_of_one_bar….f, z		
Command line only	Specifies a bar object pattern. **Number of bars** (num_of_bars) can be 1,2,3,..., as long as the pattern can fit in the image plane grid width (TGR * GRI); FFT process implies adjacent grids with the same pattern, so infinite bar patterns are possible. **Width of one bar** (width_of_one_bar) is expressed in dimensions of its geometrical image. **Range:** 0.0 to GRI * TGR/2; use this upper limit or a value significantly larger than the image width, with 1 bar, to simulate an edge.	1 bar, 0.0 width. A zero-width line.
PER distance_between_bar_centers….f, z		
Command line only	Use only with **BAR** setting, for more than 1 bar. Period of multi-bar pattern expressed as separation of bar centers in dimensions of its geometrical image. **Range:** 0 to infinity; recommended: > BAR width.	Twice the BAR width. Equal bar and spaces.
DEP min_fract_intensity….f, z		
Command line only	Use with multi-bar patterns. Defines the fractional dip to the minimum intensity in the space(s) relative to the bars at 1.0. **Range:** 0.0 to 1/(1-BGI): i.e., from no dip in intensity to a dip below background all the way to zero intensity.	1.0. Dip to background intensity (BGI) in the spaces.

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Command Syntax		
	Explanation	**Default**
BGI background_fract_int….f, z		
Command line only	Adds background intensity; compresses bar pattern to range above background. **Range:** 0.0 (no background intensity) to 1.0 (no range left for pattern intensity variations); if high values are wanted, consider using NEG.	0.0
INN bar_fract_int….f, z		
Command line only	Intensity of bar: range 0.0 to 1.0 See NEG below If NEG is N, adds intensity_transmittance to the bars If NEG is Y, subtracts from 1.0 the quantity intensity_transmittance.	1.0
PHN [ALT] bar_phase_deg….f, z		
Command line only	Phase of bar in degrees. ALT adds 180 degrees to the phase of every other bar.	0.0
BGP background_phase_deg….f, z		
Command line only	Phase of background in degrees.	0.0
NEG Yes | No		
Command line only	Inverts the object profile. Inverts the intensity pattern of the object; i.e., black becomes white and white becomes black.	No
AZI orientation_degrees….z		
Command line only	Azimuth (degrees). Specifies orientation of the bar. Rotates the bar by the specified angle. **Note**: This command can also be used to specify the spatial frequency orientation when performing MTF tolerancing; see “Defining Performance Measures” on page 20-6.	0.0
NRD number_rays_across_diameter		
Command line only	Determines ray trace grid for PAR calculation. Specifies number of rays traced across the pupil diameter for the shortest wavelength; other wavelengths are proportionately smaller to make image plane grids match - alternative to GRI. **Range:** Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both. **Note:** This command can also be used to modify the grid of rays traced through the pupil to calculate RMS, MTF, CEF, or PDL. See “Defining Computation Controls” on page 20-12 for details.	TGR/2 TGR/2 at short wavelength.

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Command Syntax		
	Explanation	**Default**
GRI image_grid_spacing….z		
Command line only	Focal plane grid for PAR calculation. Specifies grid spacing measured on the image surface; is an alternative to NRD. Use to choose a more convenient number than the default. **Range:** Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both.	Shortest wavelength * fnumber/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.)
RNA fraction_of_fill….f, z		
Command line only	Specifies relative NA (numerical aperture) of the condenser, as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. **Range:** Greater than or equal to zero. 1.0 represents the condition where the condenser just fulls the pupil.	0.0 Full coherence
RNX x_shift_of_fill….f, z		
Command line only	Specifies decenter condenser fill pattern in X direction by this fraction of the pupil.	0.0
RNY y_shift_of_fill….f, z		
Command line only	Specifies decenter condenser fill pattern in Y direction by this fraction of the pupil.	0.0
TGR num_fft_grid		
Command line only	Transforms grid size. Use to improve accuracy for systems with large or unusual obscurations, or to increase size of the image area analyzed relative to the Airy disc. **Range:** 16 or more, must be a power of 2. Unless overridden by NRD or GRI, also determines the number of rays traced in proportion to the TGR**2.	128
ERF Ej erf_name [erf_weight]		
Command line only	This command specifies an error function. Multiple error functions can be entered and are distinguished by the E qualifier. erf_name: a quoted string of up to 60 characters, that will be used for identification. erf_weight: weight used to combine error functions for purposes of calculating compensators. When multiple error functions are defined, the sensitivity table is listed for each.	If CDT has been specified: a single error function representing the vertical CD. weight: 1.0

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Command Syntax		
	Explanation	**Default**
COM Ej CDH | CDV | HVB | LRH | LRV | OVH | OVB [weight]		
Command line only	This command defines the specified lithographic metric as being a component of the Ej error function. Typically, only one component would be entered for a given Ej. Lithographic metrics are: CDH Critical dimension in the horizontal direction CDV Critical dimension in the vertical direction HVB Horizontal-vertical bias (the difference between CDH and CDV) LRH Left-right bias in the horizontal direction LRV Left-right bias in the vertical direction (top-bottom bias) OVH Overlay error in the horizontal direction OVV Overlay error in the vertical direction TCH Telecentricity in the horizontal direction TCV Telecentricity in the vertical direction If TCH or TCV is specified, the lens must have at least two focal positions (FFO, IFO, NFO). The two extreme focal positions are used to determine the telecentricity.	CDV
SCN Yes | No		
Command line only	For SCN Yes, the image is integrated over the field for each zoom position. You can specify multiple scan lines by zooming the system, where each zoom position corresponds to a scan line. For the weighting, specify the LDM weights as a function of field and zoom. CODE V allows up to 25 fields and 99 zooms so it is possible to simulate 99 scan lines where each line is modeled with 25 images.	No

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Command Syntax		
	Explanation	**Default**
SRC [Zi] [Fk] [ST1 | ST2 | ST3] filename [eff_src_radius [rot_angle_degr]]		
Command line only	Define source distribution via .INT file. Any .INT file type can be used, but if the values will be negative (e.g., for SRC ST1) the INT file type must support negative values (i.e., BIR, SUR, WFR). Background intensity value (BGI) is ignored. Default for effective radius is 1.0, and default for rotation angle is 0.0. The effective radius is in relative numerical aperture units. The source coordinate system matches the entrance pupil coordinate system. The polarization state of a source point is defined by specifying the values of the Stokes parameters (S0, S1, S2, and S3) with an .INT file. If the SRC command is used without a keyword, the S0 parameter (which is proportional to the source intensity) is defined. If the SRC command is used with the ST1, ST2, or ST3 keywords, the S1, S2, or S3 parameters are defined, respectively. Thus, complete specification of the source polarization state requires four SRC commands with four separate .INT files. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions.	Not done.
SRC [Zi] [Fk] ANN rna_min rna_max		
Command line only	Defines an annular source where the annulus is defined by a minimum relative NA (numerical aperture) of the condenser (rna_min) and a maximum relative NA of the condenser (rna_max). The relative NA (numerical aperture) of the condenser is defined as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. Examples of annulus source shapes are available in the PAR option documentation; see “Annulus and multi-pole source shape examples” on page 19-332.	Not done.

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Command Syntax		
	Explanation	**Default**
SRC [Zi] [Fk] CIR #_poles rna_min rna_max [rot_angle_degr] or **SRC** [Zi] [Fk] SEC | BUN #_poles rna_min rna_max pole_subtense [rot_angle_degr]		
Command line only	Defines a multi-pole intensity distribution where the number of poles (#_poles) is 2 or more, and the poles are spaced uniformly in azimuth. The shape of each pole is determined from the CIR, SEC, and BUN keywords, where: • CIR is a circle • SEC is a sector • BUN is bun shaped The annulus in which the poles are placed is defined by the minimum and maximum relative NA, or RNA (rna_min and rna_max). The angular subtense of the pole at the center of the source is pole_subtense (applies only to SEC and BUN). The poles are arranged so that the first pole is always at the top (+y). The entire pattern may be rotated by rot_angle_degr; the default rotation is 0.0. For all of the above sources distributions, a central spot may be added by using the RNA command. The RNA value must be greater than zero and less than rna_min. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. Examples of the CIR, SEC, and BUN pole shapes are available in the PAR option documentation; see “Annulus and multi-pole source shape examples” on page 19-332.	Not done.

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Command Syntax		
	Explanation	**Default**
SRC POL [RAD | LIN | MIX | CIR | CIL] [fraction_pol]		
Command line only	Defines the polarization that goes with the intensity pattern. If omitted, the source is unpolarized. The polarization is defined for the first pole in the unrotated intensity pattern and rotates with any rotation of the pattern. The fraction of polarization (fraction_pol) defaults to 1.0. If a number between 0 and 1 is entered, the remainder goes into the orthogonal state. A value of 0.5 is equivalent to an unpolarized source. A value of 0.0 is equivalent to orthogonal polarization. The types of polarization are: • RAD is radial. This is the default. • LIN is linear in X. • MIX is linear in X for the first pole, but changes for each pole. • CIR is right circular. • CIL is left circular. If RNA is included in the pattern, it receives the same polarization as the first pole. RAD is linear polarization along a radius of the pattern, and varies with position in the pattern. LIN applies the same polarization to each pole. MIX (sometimes called mixed or segmented polarization) applies a different linear polarization to each pole, depending on position; the angle of polarization stays aligned with a radius. For example, for a quadrapole with MIX and a fractional polarization of 1.0, poles 1 and 3 would have linear polarization in X, and poles 2 and 4 would have linear polarization in Y. Examples of the SRC POL command are available in the PAR option documentation; see “Annulus and multi-pole source shape examples” on page 19-332.	Not done.

Discussion of Input and Computations

What to Include in the LDM Data

Tolerances are entered in the LDM; if TOR is run without them, the LDM default set (DEF TOL SA) plus one focus compensator (CMP DLZ SI) is generated.

Along with the tolerances, compensators may be defined in the LDM. These are parameters which model the assembly process. Any tolerance type can be specified as a compensator. Such things as seeking best focus by shifting the image distance and tilting the image surface to remove the defocus effects of centering tolerances are commonly done. Refocusing of relays, objectives and eyepieces is common, also. The value of the compensator represents the limit of allowed change in a compensator; if no value is supplied, this limit is 20X the default for the corresponding tolerance type.

Specific tolerancing controls allow TOR to select the most effective set of compensators for your system. The **Singular Value Decomposition (SVD) Threshold** and **Used Compensators** controls in the **System Data**

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window (SVT and MCP commands, respectively) regulate the compensators used to compensate all the tolerances. See “Defining Tolerance Controls” on page 3-60 for details about these commands. In addition, you can specify which compensators must be used, and which can be dropped from the system. This is done using the **Compensator Use Control** field in the **Surface Properties** window, on the **Tolerances** page. From the command line, use the CMP command. For details, see the CMP command description under “Other Tolerance Controls” on page 8-23.

TOR uses apertures as specified with the CA command (**Lens** > **System Data** menu, **System Settings**, **Apertures Used** field) for determining ray bundles for ray tracing. In addition, some tolerances use a circular diameter as part of their definition. These tolerances are DLF, IRR (CYN and CYD), TIR (TRY and TRX), DLS, and RAG. These tolerances are defined with a single, centered, circular aperture whose radius is the maximum of the following:

- Radius of all circular apertures
- Semi-diagonal of all rectangular apertures
- Semi-diameter of major axis of all ellipse apertures

These are evaluated for all clear apertures, including all labels, but ignoring any decenter values. The result is the same value as is returned with the Macro-PLUS database item for maximum aperture (MAP Sk). If you wish the tolerance to use a different aperture diameter, this can be simulated by scaling the tolerance value. DLF, IRR, DLS, and RAG scale as the square of the aperture diameter, and TIR scales linearly with aperture diameter.

If you are going to analyze the effects of distortion (**DST**) or correct boresight (**BOR; i.e., line-of-sight errors**), it is best to have the first field represent the center of your image format; for most situations, this would be on-axis.

Any apodization (Gaussian or user-defined) is used in TOR calculations, unless you are using CEF tolerancing; in that case, apodization defined by INT files is not recognized.

TOR with Polarization Ray Tracing

TOR will calculate changes to the MTF or coupling efficiency (CEF) assuming a polarized input beam when polarization ray tracing is enabled (POL Y, or **Activate Polarization Ray Tracing** in the **System Data** window). The polarization dependent loss (PDL) calculation always assumes a polarized input beam.

CEF Tolerancing

For CEF tolerancing, the output fiber location is defined in the LDM with the FLO command, in either a fixed (FLO FIX) or compensated (FLO CMP) position. In the GUI, choose the **Lens** > **System Data** menu, and go to the **Output Fiber** page in the **System Data** window to define the output fiber location. See “Defining Output Fiber Location” on page 3-56 for details.

Note: The FLO CMP command defines the nominal position of the output fiber (i.e., if no additional offsets are applied, the output fiber is located at the nominal chief ray intercept at the image surface and oriented along the chief ray direction for each input field). Thus, the CMP mode yields a static output fiber position. It is unrelated to the compensating parameters used in TOR for simulating the manufacturing and assembly process, and does not affect the tolerance compensation process.

Usage

A grid of rays is traced through the pupil to calculate RMS, MTF, CEF, or PDL. The default number of rays across the pupil diameter is 32, which is suitably accurate for most cases. Studies have shown that even 10 rays can be used effectively for rough tolerancing. To change the number of rays, use the **NRD** command. Execution time is proportional to the number of rays traced (or to the square of **NRD**).

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Performance Measures and Compensation Controls

If MTF tolerancing is required, a spatial frequency (**FRE**) must be entered in units of line-pairs/mm. If no orientation (**AZI**) is entered, 90.0° (tangential) is assumed. Different values may be entered for each field and zoom position, if desired. If no frequency is entered, the performance measure will be RMS wavefront error.

The **MPR** command allows you to tolerance your lens system based on fiber coupling efficiency (CEF) or polarization dependent loss (PDL) requirements. The MPR command operates under the following conditions:

- The output fiber mode is assumed to be Gaussian.
- The input fiber mode is simulated by Gaussian pupil apodization, defined by PUI, PUX, and PUY. A uniform pupil may be used, but this is typically not appropriate for fiber systems. Apodization defined by INT files is not recognized.
- The output fiber is located at the image surface vertex and oriented along the Z-axis. To reposition or reorient the nominal output fiber, use the **FLO** command in the LDM. In the GUI, this is defined in the **System Data** window (**Lens** menu), on the **Fiber Location** page. For complete details about defining the output fiber location in both the GUI and on the command line, go to “Defining Output Fiber Location” on page 3-56.
- Weights specified with WTF and WTW commands are used for relative weighting of the different zooms, fields, and wavelengths.
- If multiple wavelengths are used, the output gives the weighted average of coupling efficiency over wavelength.

Compensators may be labeled so that they work with a similarly labeled subset of the tolerances, or the **BOR** command. If compensators have been entered, the relative weighting of the fields and zoom positions affects the compensation. The default values are the LDM weights. These may be changed with the **WTF** command; using 0 for any field omits calculation and output.

In systems where it is desirable to keep the boresight fixed, the compensation can be constrained to do so. The **BOR** command specifies that all, or designated groups, of the compensators which were previously entered, are used to keep distortion at the designated images fixed, in addition to any other compensation.

As an alternate to using **BOR**, which holds the change in chief ray height to zero for a specified field, a general weight on distortion can be included in the compensation calculations (**WTD**). The weight on distortion can be specified separately for the X and Y directions. A weight of zero does not include distortion in the compensation calculations. A non-zero weight will have the effect of holding down distortion at the expense of MTF or RMS. Since the distortion and MTF or RMS are in different metrics, it may be difficult to know what weight to use, so several runs may be necessary. **WTD** does not cause retracing of the system, so several runs may be done quickly.

The variation of the MTF, the square of the RMS or CEF is quadratic in the tolerance and therefore has both a linear and quadratic term. Both of these are used in the compensation process to minimize the change in MTF, RMS, or CEF. In some cases, it is useful to change the relative weighting of the linear term with respect to the quadratic term. This is done with the **WTS** command. It is recommended that this not be used under normal circumstances. It has been most useful when the linear terms are large and there is more than one compensator.

In a rotationally symmetric system, only one side of the field is normally entered. In the compensation calculations, the performance on the opposite side of the field is determined from the performance at the given fields. This is necessary for the correct determination of the compensators. When a system is not symmetric, all the fields which affect the calculation must be entered. However, there are cases where the system is optically symmetric but is considered asymmetric by CODE V. The most common case is a folded, rotationally symmetric system. To avoid having to enter additional fields (and increase computation time), the **SYM** command may be used.

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Two commands, **CNS** and **WTC**, allow you to limit the maximum absolute value of the X, Y, and Z shifts of the center of the optimally compensated, best-fit reference sphere for each tolerance in the lens system. The **CNS** command applies a Lagrange multiplier constraint on tolerances; it constrains the X, Y, and Z shifts of the center of the best fit reference sphere so that their absolute values are less than or equal to a specified maximum value. The **WTC** command applies a weighted constraint on tolerances. When the weight is non-zero, the X, Y, and Z shifts of the center of the best fit reference sphere are considered in the compensation calculation. The larger the weight, the lower the absolute magnitude of the shift will be, at the expense of less optimal compensation that results in greater RMS wavefront error. Lagrange and weighted constraints may both be used in the same lens. However, keep in mind that you may only have as many active Lagrange-type constraints as there are compensators. Also remember that boresight constraints and compensator limit constraints are also treated as Lagrange constraints, and, if active, they reduce the number of CNS constraints that can be simultaneously held. If there are more constraint violations for a given tolerance than there are compensators, the excess violations are ignored, and this will in general lead to solutions where one or more constraints fail to satisfy their targets. Also note that when rounding of tolerances is allowed, the CNS constraints will not generally be held exactly at their limits. Instead, they will generally have values less than their limits. This is because CODE V computes the unrounded tolerance with the constraints held, then rounds down the tolerance to the next convenient value. Rounding the tolerance down will in general cause the constraint value to decrease as well, so that the CNS constraint is not active in the final solution.

Computation Controls

TOR may be run in sensitivity mode (**SNS**) or inverse sensitivity mode (**INV**). The default is **INV**. In sensitivity mode, changes in the performance measure are calculated for the values of the tolerances entered in the LDM. In inverse sensitivity mode, the tolerance values are determined such that the maximum degradation in the performance measure is less than a specified value. The default value is 0.01 for RMS wavefront, or -0.01 for MTF, CEF,or PDL, and may be changed by entering a value on the **INV** command. (For coupling efficiency with DB set to Yes, the entered value is the change in CEF converted to decibels.) Each of the tolerances has minimum and maximum limits imposed on it. In the inverse mode, these values are adhered to so that, in some cases, the change in performance measure may exceed, or be less than, the specified value. In addition, the tolerance is rounded to a reasonable value. The minimum value, maximum value and rounding increment may be modified by the user (**LIM**). The **ROU** command may be entered to eliminate rounding of the tolerances entirely.

In the inverse sensitivity mode, two-dimensional tolerances such as DEC, BTI, etc., are constrained so that the tolerance values of the two components are the same (or held to the specified ratio). If you wish to decouple the two components, use the DCP qualifier on the **INV** command. In this case, the statistical summaries will assume that the two components are independent. DCP will also release the constraint that the ratio of fringe error (DLF) to irregularity error (IRR) lie between 2.0 and 4.0.

Zernike Polynomial Controls

You can define the TOR error function in terms of Zernike polynomial coefficients, which you then use to determine tolerances. The Zernike polynomial types include standard Zernikes (ZRN), fringe Zernikes (ZFR), and extended fringe Zernikes (ZFE). They can be fit to the entrance pupil, exit pupil, or exit sphere. The ERF command allows you to specify one or more error functions. Each error function is a weighted sum of squares of the specified Zernike coefficients and/or distortion using either the entered weights or the default weights. When you use multiple error functions, they will be combined in a weighted sum of squares mode and used as the error function for the compensation calculations. The COM command allows you to specify a coefficient as a component of a given error function. You can also enter distortion into the error function using the COM DIX and COM DIY commands. Distortion values are determined from the C2 and C3 coefficients. The units of distortion are determined by the UNI command. For details on all these commands, see “Defining Zernike Polynomial Controls” on page 20-10.

See “Zernike error functions in TOR” on page 20-57 for an example of how to use this feature.

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Output Controls

The standard output consists of an entry for each tolerance giving the change in performance measure and the compensators, if any. This output may be modified in several ways. The **FUL** command lists the linear and quadratic terms for each tolerance describing the variation of the performance measure with that tolerance. In most systems, there are a few driving tolerances and the rest have very little effect on the performance measure. To avoid outputting the ineffective tolerances, use the **SEL** command. Those tolerances which change the performance measure by less than the tolerancing criterion (normally 0.01), will be deleted from the output. The factor may be changed by entering a value with the **SEL** command. The **DST** command gives a list of changes in distortion for each of the tolerances. It is calculated differently for RMS, MTF, CEF, and PDL. For MTF, CEF, and PDL it is the deviation of the chief ray, while for RMS it is the average deviation of the entire bundle of rays. In all cases, it is averaged over wavelength. If a label is entered with the DST command, any compensators with the same label will be used in the calibration of the distortion. This is in addition to the scale change, image rotation and lateral shift compensators which are always used to calibrate distortion. For example, in a photogrammetric lens it is appropriate to specify the tilt of the boresight axis as a calibration parameter. In this case, the compensator BTI S1..I would be entered with the same label as in the DST command. For RMS tolerancing, the **XYZ** command adds a table of reference sphere shifts to the output. If **XYZ Yes** is entered, a table is listed that summarizes the probable changes in the X, Y, and Z shifts of the center of the best fit reference sphere. If **XYZ All** is entered, shifts are listed for each optimally compensated tolerance, in addition to the summary listing of the probable changes. The table is output separately for each field and zoom position, immediately following the table of X and Y distortion values, if DST is requested. For CEF tolerancing, the **DB** command converts the coupling efficiency to units of decibels subject to the specified threshold value.

TOR sensitivity, distortion, and performance summary output can be written to a specified buffer (WBF command). The data in the buffer can then be exported (BUF EXP) for further analysis outside of CODE V. The WBF SEN command writes the TOR sensitivity tables, including sensitivity coefficients. The WBF DST command writes the TOR distortion tables, including contributions from each tolerance, as well as the summary list of X and Y distortions. The WBF PER command writes the TOR performance summary data. The WBF ZRN command writes the Zernike sensitivity data, if the Zernike error function has been specified.

The cumulative probability plot(s) created by TOR are based on a simulated Monte Carlo of the wavefront differential data. Note that this Monte Carlo simulation does not physically perturb the lens prescription and analyze the result; if this is desired, use the Monte Carlo tolerancing feature (**Tolerancing** > **User - Monte Carlo** menu). Within TOR, the Monte Carlo simulation applies random variations to wavefront differential coefficients for every tolerance (and pair of tolerances) in the system. If you choose Monte Carlo output (WBF MC), the performance results for each trial (at each field and zoom) are exported to the designated worksheet buffer.

Note that you can write all of the TOR data types described in the preceding paragraphs to the same buffer.

Linewidth Computation Controls for 1D Partial Coherence Tolerancing

Tolerancing metrics can be based upon the critical dimension (CD) of an image using the **CDT** command in TOR. To this end, a number of PAR commands are also available in TOR, so that partially coherent imagery can be computed for the CD computations. Several lithographic error function components upon which tolerancing criteria can be based are available using the **COM** command, including critical dimension in the horizonal and vertical directions, overlay errors, and telecentricity. Further, multiple error functions (based upon CD computations) can be used to specify a single figure of merit, with each error function component (**COM**) listed within an error function (**ERF**) and weighted appropriately. Scanning (**SCN**) can also be taken into account by zooming the system, with each zoom being a single scan line. PAR commands used to define the object and source are also available in TOR to facilitate partial coherence tolerancing (**BAR**, **PER**, **DEP**, **BGI**, **INN**, **PHN**, **BGP**, **NEG**, **AZI**, **NRD**, **GRI**, **RNA**, **RNX**, **RNY**, **TGR**, and **SRC**).

When using NRD, TGR, and GRI to adjust the ray grid used in partial coherence tolerancing, it's useful to understand more about the relationships between these three commands; see "Grid Considerations for Diffraction Calculations in CODE V" on page 19-358 for details.

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See “Examples” on page 20-51 to see several examples of using the linewidth computation controls for partial coherence tolerancing.

Probability Density Functions

The form of the probability density function can be specified by tolerance group (**PDS**, **PDD**, **PDI**). Tolerances are grouped into one of three general tolerance groups, scalar tolerances, decentration tolerances, and cylindrical irregularity tolerances. The tolerance groups comprise the following tolerances.

One-dimensional tolerances (specified with **PDS**)

DLF, DLT, DLN, DLV, DLR, DLS, DLC, DAK, DAA, DAB, DAC, DAD, DAE, DAF, DAG, DAH, DAJ, HOM, AXG, RAG, DLZ, DLG, BRL, DSZ, DOL, and all coupled tolerances

Two-dimensional tolerances (specified with **PDD**)

DEC (DLX, DLY), TIL (DLA, DLB), TIR (TRX, TRY), STI (STX, STY), BTI (BTX, BTY), DIS (DSX, DSY), ROL (RLX, RLY)

Cylindrical irregularity tolerances (specified with **PDI**)

IRR (CYN, CYD)

For each group, the probability density function can be specified as one of three predefined forms or specified by its second and fourth moments. The choices of predefined function forms are as follows.

UNI	Uniform probability across the tolerance range. The uniformity is in 1D or 2D, depending on the tolerance type. This is the default density function for scalar and irregularity tolerances and for all coupled tolerances.
GAU	Gaussian probability with a specified truncation value at the end points of the tolerance range. To specify truncation at the $k\sigma$ point, where σ is the Gaussian standard deviation, input $\exp(-k^2/2)$. For example, to truncate at the 2σ point, input e^{-2}, which is equal to 0.135. The Gaussian probability density function, with a truncation value of 0.135, is the default density function for all decentered tolerances.
END	Tolerances can only take on the values of the end points of the tolerance range, i.e., ± tolerance value.

The probability density can also be defined by specifying its second and fourth moments. The moment values are entered for a tolerance value of 1.0. The moments are properly scaled inside TOR for the actual tolerance values. The nth moment ν_n is defined as

$$\nu_n = \frac{\int_D x^n p(x)dx}{\int_D p(x)dx}$$

where D is some domain over which p(x) is defined. The equivalent moments for the default density distributions used are given in Table 2 (the Gaussian is truncated at the $1/e^2$ point).

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Table 2. Second and fourth moments for different probability densities

	1D		2D	
Density function	ν_2	ν_4	ν_2	ν_4
UNI	0.3333	0.2000	0.5000	0.3333
GAU	0.1934	0.0885	0.3435	0.1870
END	1.000	1.000	1.000	1.000

For more detail on probability densities and moments, refer to "A Statistical Approach to Lens Tolerancing," by Donald G. Koch, *Proc SPIE*, Vol. 147, pp. 71-82 (1978).

If **INV** DCP is used to decouple the decentered and irregularity tolerances, then **PDD** and **PDI** will use the 1D form of the specified density distribution rather than the 2D form.

Interactive Tolerancing

After running TOR you may find that you want to make further changes in the values of tolerances and rerun TOR until you get the optimum set of tolerance values for the desired performance level. Interactive tolerancing is a unique feature that allows you to change tolerance values and immediately see the effect on predicted performance and compensator movement. With immediate feedback you can iterate TOR rapidly until you obtain satisfactory results.

Rerunning TOR rapidly is possible because interactive tolerancing reuses sensitivities that have already been computed. Sensitivities are computed from differential calculations run as part of ray tracing the pupil grids. These sensitivities can be reused as long as the conditions associated with their calculation do not change; thus, for example, changing tolerance values in the LDM does not require recalculation, while adding new tolerances does require recalculation. (See "Rerunning TOR: Recalculation and Speed of Interactive Tolerancing" on page 20-44 below for more detail on which changes will initiate recalculation.)

To use interactive tolerancing you must first perform a standard **TOR** run (**Analysis > Tolerancing > MTF**, **RMS**, **CEF**, or **PDL**). You can then access it at **Analysis > Tolerancing > Interactive Tolerancing**.

Using the Interactive Ray Tolerancing Dialog Box

Restore a lens and run one of the standard TOR options, such as **Analysis > Tolerancing > MTF**, **RMS wavefront error**, **Fiber Coupling Efficiency (CEF)**, or **Polarization Dependent Loss (PDL)**. (If you will be closing and restoring the lens before you use interactive tolerancing, save the lens with **Save Lens As** and rename it to avoid overwriting the original lens. You can then reuse the tolerancing values you have set thus far.)

To access the Interactive Ray Tolerancing dialog box, choose the Analysis > Tolerancing > Interactive Tolerancing menu. This dialog box displays three tabs, the Tolerance Sensitivities tab, the Centered Tolerances tab, and the Decentered Tolerances tab. On all three tabs, the relevant tolerances are shown in the spreadsheet in the top section of the tab and the performance summary and compensator data are shown in the two sections at the bottom of each tab. The same performance summary and compensator data is repeated on each tab for convenience.

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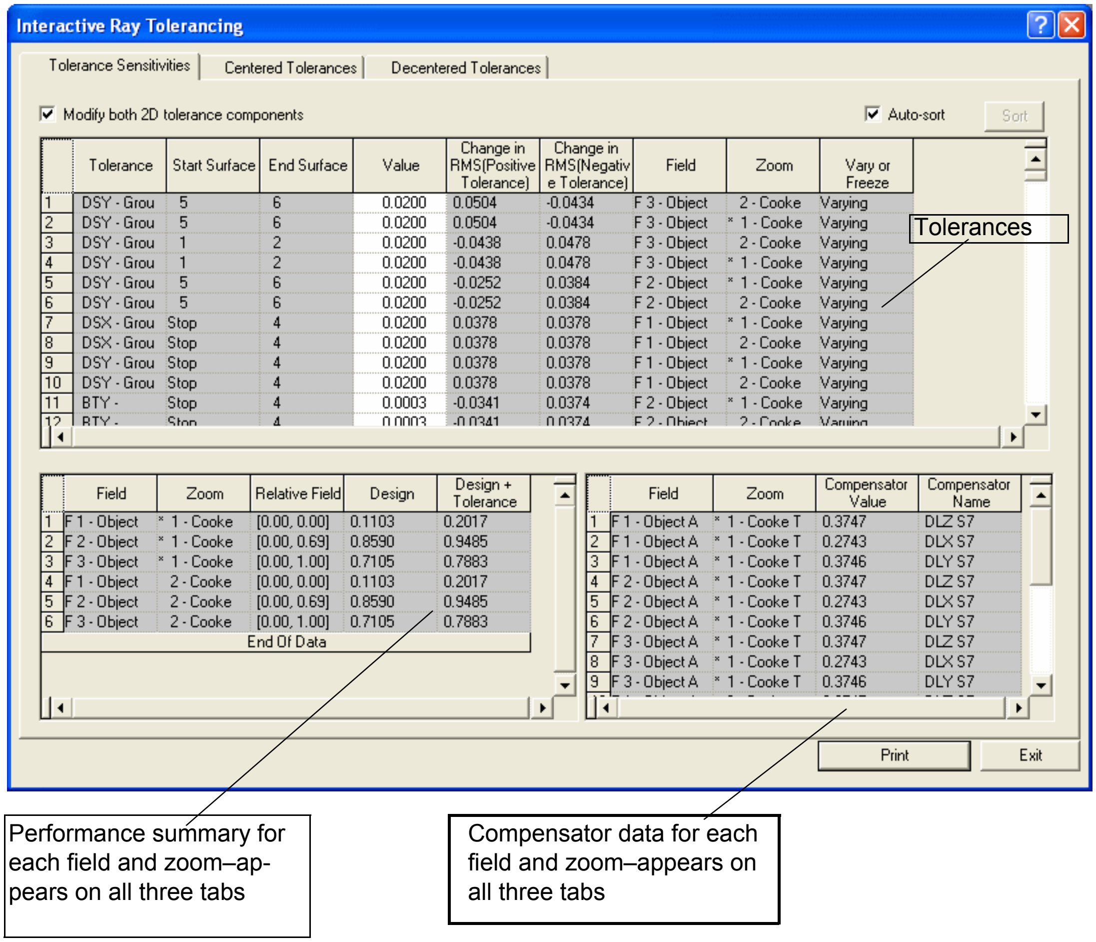

Most of the data that appears in the Interactive Tolerancing dialog box is read-only and indicated in gray. The individual tolerance values on the Tolerance Sensitivities tab and the Centered Tolerances tab are editable, which is indicated in white. Changing these values will change the read-only data as appropriate.

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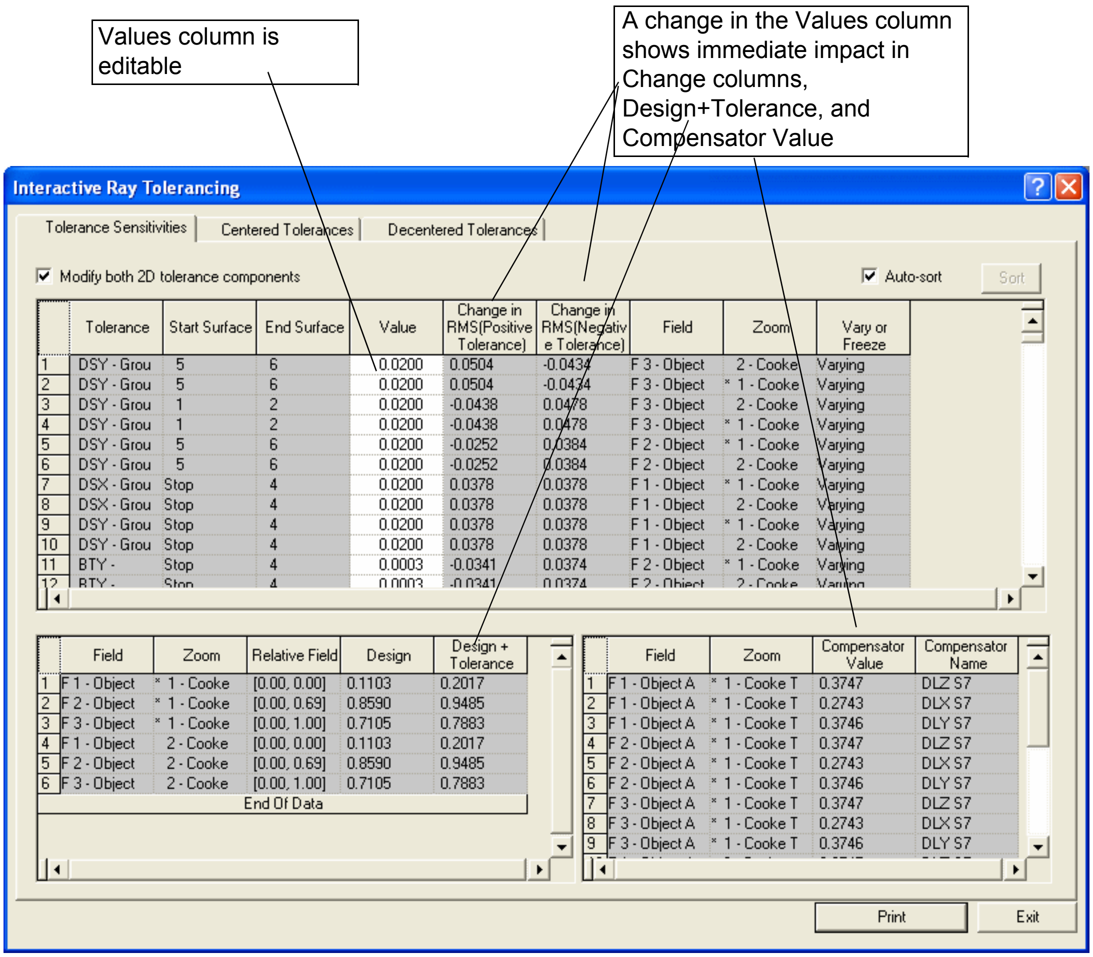
Tolerance Sensitivities Tab

The Tolerance Sensitivities tab includes a Value column, which corresponds to the tolerance value. This is the data that you would typically modify when using interactive tolerancing. If you change a value in this column, you can immediately see its effect to the right in the columns labeled Change in XXX (Positive Tolerance) and Change in XXX (Negative Tolerance), where XXX corresponds to the current performance metric (i.e., MTF, RMS, CEF, or PDL).



The Value column shows a symmetrical tolerance value, i.e., if the tolerance value is 0.5, that would indicate an allowance of $\pm$0.5 for the associated constructional parameter, e.g., $\pm$0.5 mm of surface radius for an RDY tolerance. The change columns tell you what the effect would be on performance for the maximum change in either direction. For example, if your tolerance value is 0.5 and you change it to .75, the Change in RMS (Positive Tolerance) will tell what change in RMS wavefront error would result from the maximum positive (+0.75) deviation for that tolerance type, and the Change in RMS (Negative Tolerance) will tell you what change would result from a the maximum negative (-0.75) deviation for that tolerance type. To further this example, if the tolerance value were for lens thickness (DLT) with a nominal value of 5mm, an increase by +0.75 (the "Positive Tolerance") would display the change for RMS if the lens were at its maximum acceptable thickness of 5.75 and a decrease of -0.75 (the "Negative Tolerance") would display the change for the RMS if the lens were at its minimum acceptable thickness of 4.25mm.

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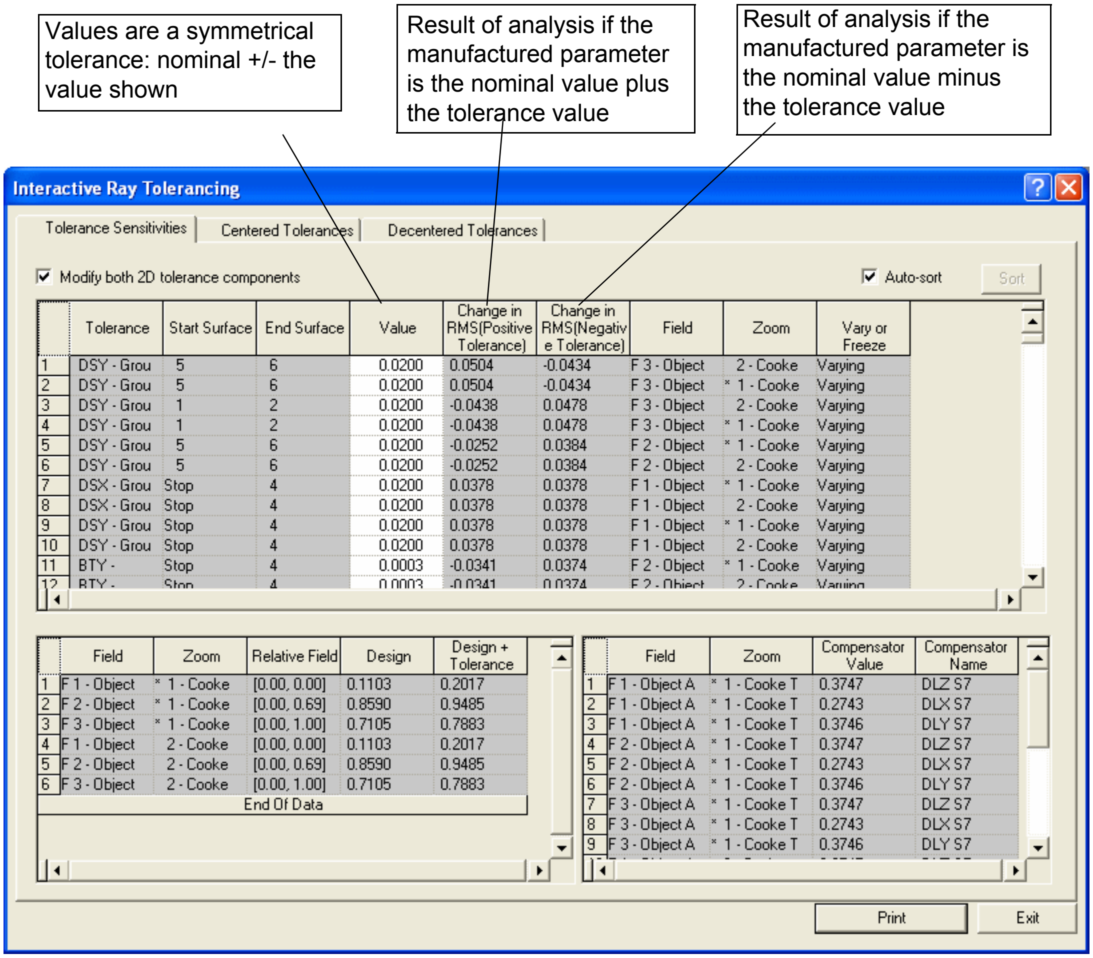

Changing Tolerance Values

Two features on the **Tolerance Sensitivities** tab facilitate changing tolerance values: modifying both components of 2D tolerance and the ability to enable or disable automatic sorting (Auto-sort).

Modify Both Components of a 2D Tolerance

CODE V supports both scalar and vector tolerance types. Scalar tolerances have only a magnitude value (e.g., delta thickness, DLT). Vector, or 2D tolerances, consist of a magnitude and an orientation (e.g., barrel tilt, BTI, which have a magnitude in radians, and the tilt axis can be oriented in any direction on the x, y plane). CODE V treats 2D tolerances as having a magnitude and arbitrary orientation for its performance prediction. However, to analyze tolerance sensitivities, it decomposes 2D tolerances into two components (e.g., BTI into BTX and BTY and IRR into CYN and CYD).

By default, when you change one component of a pair of 2D tolerance values (e.g., DSX or DSY), both components will be updated. To change each component individually, click the **Modify both 2D tolerance components** check box to disable it.

Enable or Disable Automatic Sorting

By default, the list of tolerances will be reordered as soon as you change a tolerance value, thus changing your display. They are sorted based on the worst degradation in either of the two columns **Change XXX (Positive Tolerance)** and **Change XXX (Negative Tolerance),** where XXX is the performance metric. Note that there

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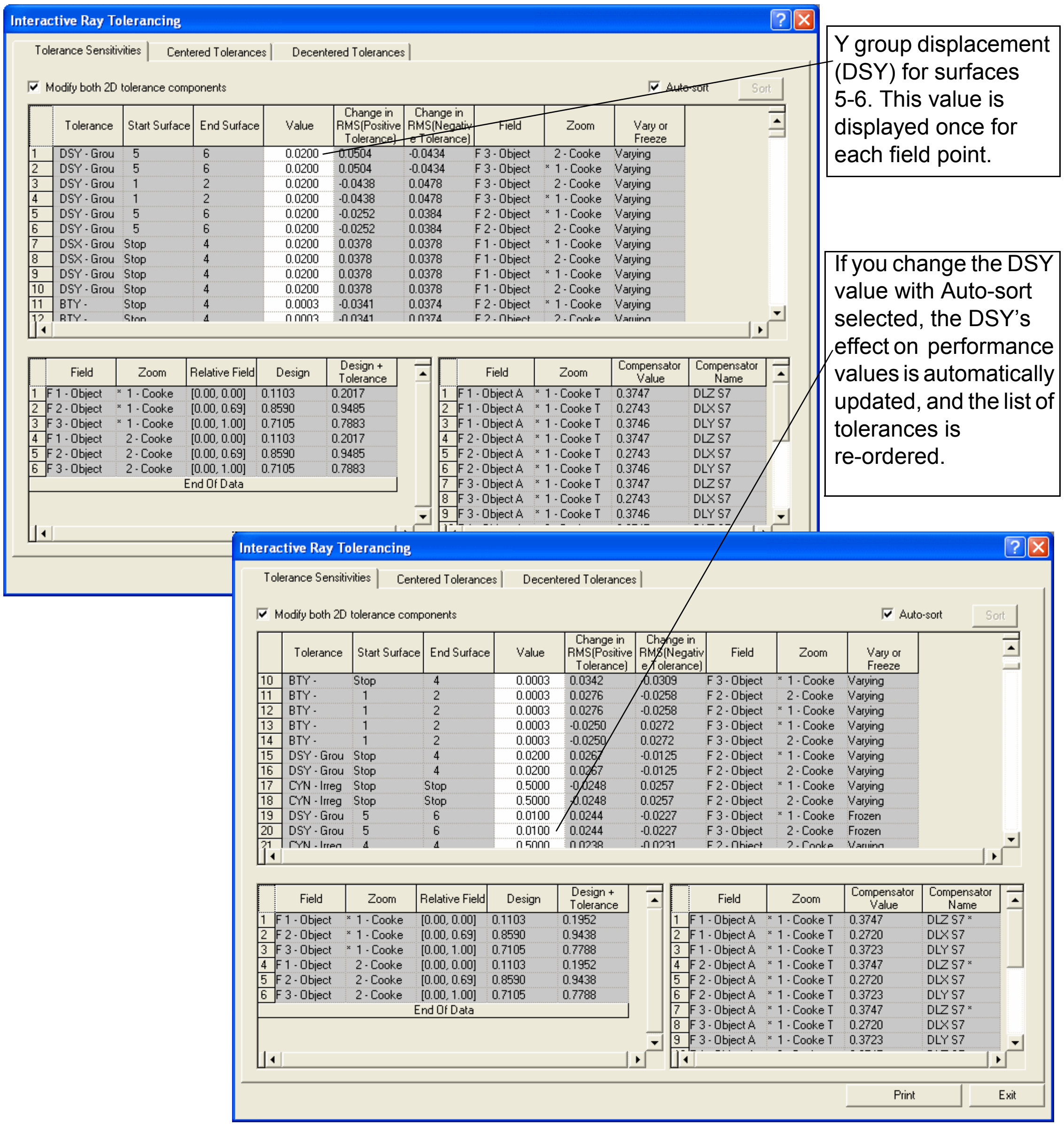
is a separate row for the impact of each tolerance on every field and zoom, which means that the same tolerance may appear multiple times.

To disable automatic sorting, click the **Auto-sort** box so that it is no longer checked. The **Sort** button will become available so that you can sort the values whenever you choose.

The following figure shows an example of automatic sorting for RMS.



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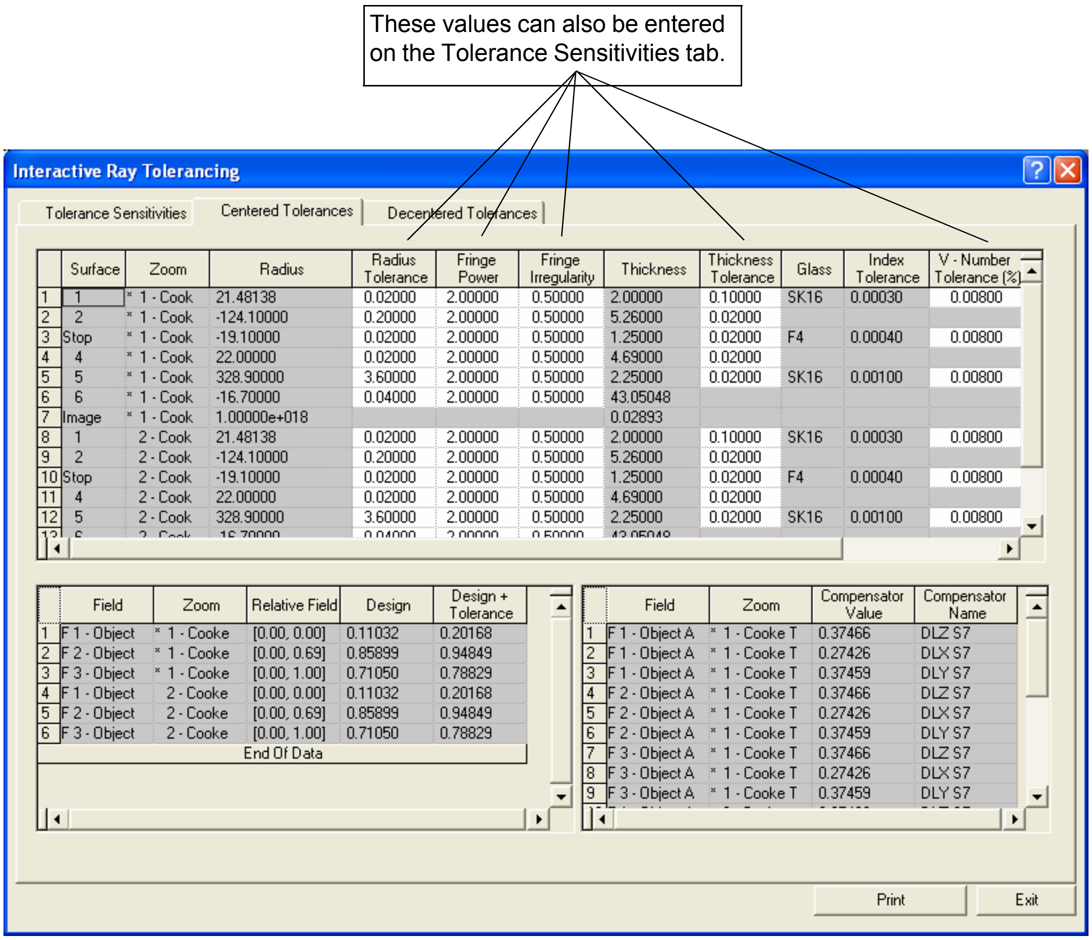
Centered Tolerances Tab

For your convenience, some of the single surface tolerance types that can be changed in the Value column on the Tolerance Sensitivities tab are also available on the Centered Tolerances tab, and will update in both places wherever you enter the value. On the Centered Tolerances tab you can change the Radius Tolerance (DLR), Fringe Power (DLF), Fringe Irregularity (IRR), Thickness Tolerance (DLT), and V - Number Tolerance (%) (DLV) columns. (See “Tolerance Type and Command Summary” on page 8-4 for more information on these tolerance types.)



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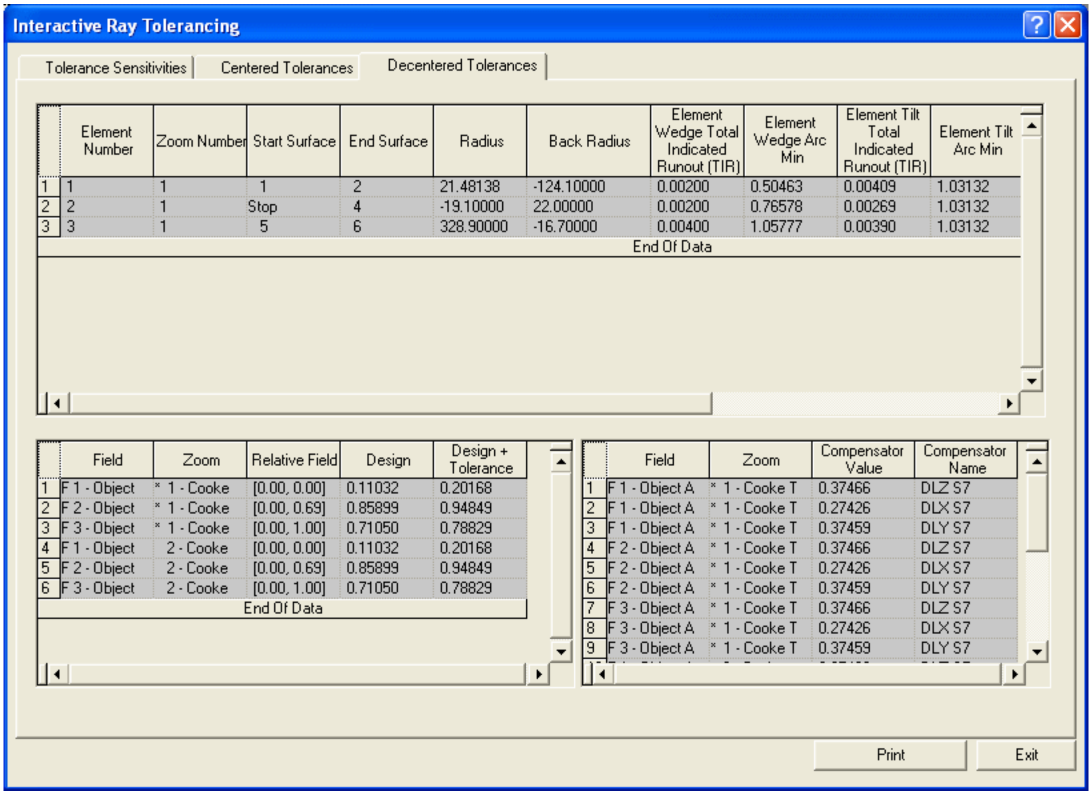
Decentered Tolerances Tab

This tab displays the asymmetric (decentered) tolerances, which are listed by element, not by surface. The tolerance values cannot be changed on this tab, as values shown may be the result of multiple tolerance values. To change the decentered tolerance values, use the Tolerance Sensitivities tab.



	Element Number	Zoom Number	Start Surface	End Surface	Radius	Back Radius	Element Wedge Total Indicated Runout (TIR)	Element Wedge Arc Min	Element Tilt Total Indicated Runout (TIR)	Element Tilt Arc Min
1	1	1	1	2	21.48138	-124.10000	0.00200	0.50463	0.00409	1.03132
2	2	1	Stop	4	-19.10000	22.00000	0.00200	0.76578	0.00269	1.03132
3	3	1	5	6	328.90000	-16.70000	0.00400	1.05777	0.00390	1.03132
						End Of Data				

	Field	Zoom	Relative Field	Design	Design + Tolerance
1	F 1 - Object	* 1 - Cooke	[0.00, 0.00]	0.11032	0.20168
2	F 2 - Object	* 1 - Cooke	[0.00, 0.69]	0.85899	0.94849
3	F 3 - Object	* 1 - Cooke	[0.00, 1.00]	0.71050	0.78829
4	F 1 - Object	2 - Cooke	[0.00, 0.00]	0.11032	0.20168
5	F 2 - Object	2 - Cooke	[0.00, 0.69]	0.85899	0.94849
6	F 3 - Object	2 - Cooke	[0.00, 1.00]	0.71050	0.78829
			End Of Data		

	Field	Zoom	Compensator Value	Compensator Name
1	F 1 - Object A	* 1 - Cooke T	0.37466	DLZ S7
2	F 1 - Object A	* 1 - Cooke T	0.27426	DLX S7
3	F 1 - Object A	* 1 - Cooke T	0.37459	DLY S7
4	F 2 - Object A	* 1 - Cooke T	0.37466	DLZ S7
5	F 2 - Object A	* 1 - Cooke T	0.27426	DLX S7
6	F 2 - Object A	* 1 - Cooke T	0.37459	DLY S7
7	F 3 - Object A	* 1 - Cooke T	0.37466	DLZ S7
8	F 3 - Object A	* 1 - Cooke T	0.27426	DLX S7
9	F 3 - Object A	* 1 - Cooke T	0.37459	DLY S7

Performance and Compensator Tables

All three tabs show the performance summary table and compensator summary table at the bottom of the Interactive Tolerances dialog box.

Performance Summary Table

The performance summary table (on the bottom left) lists the nominal and "as-built" performance (assuming a 2σ probability, i.e., 97.7% of systems will have this performance or better) for each field and zoom. This table automatically updates as tolerance values are changed during interactive tolerancing.

Compensator Summary Table

The compensator summary table (on the bottom right) lists the +/- compensator range required for each defined compensator at each field and zoom. Typically, common compensation is used across field and zoom, but independent compensation can be requested (Lens > System Data > Tolerance Controls > Independent Compensators). This table automatically updates as tolerance values are changed during interactive tolerancing.

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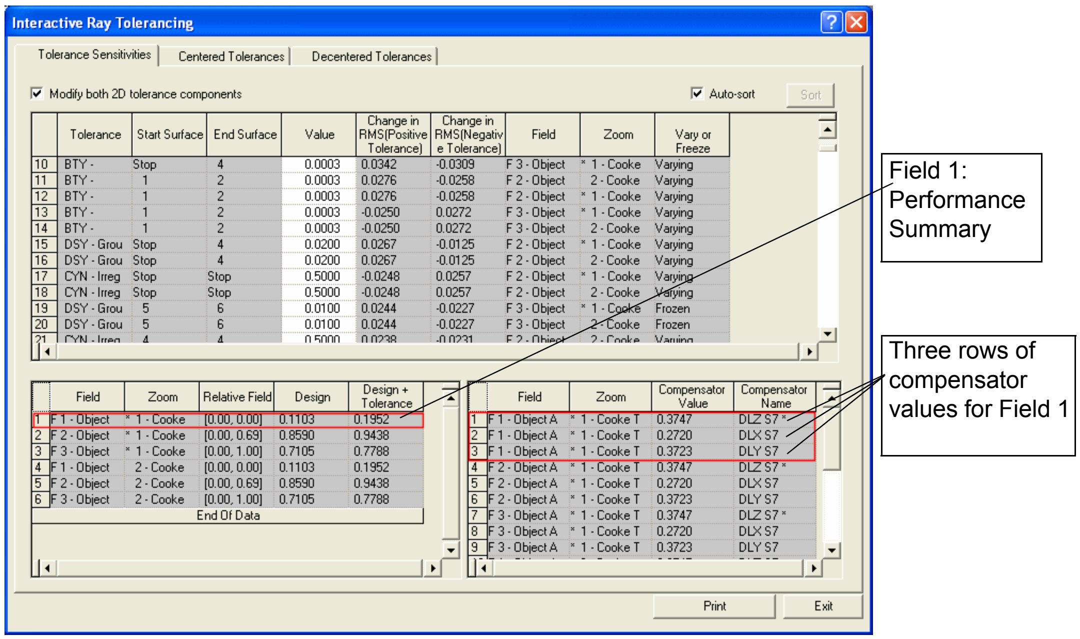

Note: Columns without data are automatically hid. To show all columns, right-click on the table and select **Unhide All**.

Reviewing Tolerance Data

Any tolerance value changes that you make in the Interactive Tolerances dialog box will update the values that appear on the Tolerances page of the Surfaces Properties dialog box (right-click on a surface in the **Lens Data Manager**, select **Surface Properties**, and select the **Tolerances** page). Tolerances changed during interactive tolerancing are frozen, so that they will not change during subsequent inverse sensitivity tolerancing.

They will also appear in the Tolerances and Compensators review table, which you can open at **Review** > **Tolerances**.

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Printing Reports

You can print the following reports based on the data in the Interactive Ray Tolerancing window:

- Tolerance Sensitivities
- Centered Tolerances
- Decentered Tolerances
- Performance Summary: Design
- Performance Summary: Compensators

As with all interactive tolerancing features, you must first perform a standard **TOR** run (**Analysis > Tolerancing > MTF**, **RMS**, **CEF**, or **PDL**). You can then access the Interactive Ray Tolerancing window at **Analysis > Tolerancing > Interactive Tolerancing**.

To print this data, click the **Print** button on the lower right of the Interactive Ray Tolerancing window and the **Select Tolerances to Print** dialog box will open with the following selections:

- The first three selections will print the data in the top section of each tab: **Tolerance Sensitivities**, **Centered Tolerances**, and **Decentered Tolerances**.
- The **Performance Summary** selection prints a table listing the nominal and "as-built" performance for each field and zoom position.
- The **Compensator Summary** selection prints a table listing the compensator range required for each defined compensator at each field and zoom.

By default, all output selections are checked. Accept all of them or click any unwanted options to deselect them. Click **OK**. A separate **Print** dialog box will open for each of the tables you have requested. Click **OK** to print each report.

If you think you may have too many columns for the width of one page (the last one or more columns may spill onto another page), you may need to

- print the tables in landscape mode
- print them to legal size paper in landscape mode
- set the graphics scaling to less than 100%
- print only selected consecutive columns (Click on the column heading of the first column you want to print and **Shift-click** to select the last column. Then, in the Print dialog box, choose **Selection** for the print range if your printer offers that option, and click **OK** to print.)

Alternatively, you can save the windows as a text file and print it from a program such as Microsoft Excel.

Save Reports for Later Use or Comparison

Saving the data in the Interactive Ray Tolerancing window may be helpful if you want to have access to the data for various tolerance sensitivities in order to compare and contrast them. You can open the data in a tab-delimited spreadsheet program such as Microsoft Excel under different file names and change the page setup as you wish.

The **Save Window As** button saves the same five reports as those printed by the Print button. They are saved as tab-delimited ASCII files.

- Tolerance Sensitivities
- Centered Tolerances

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- Decentered Tolerances
- Performance Summary: Design
- Performance Summary: Compensators

As with all interactive tolerancing features, you must first perform a standard **TOR** run (**Analysis** > **Tolerancing** > **MTF**, **RMS**, **CEF**, or **PDL**). You can then access the Interactive Ray Tolerancing window at **Analysis** > **Tolerancing** > **Interactive Tolerancing**.

To save this data, click the **Save Window As** button at the bottom of the Interactive Ray Tolerancing window and the **Select Tolerances to Print** dialog box will open with the following selections:

- The first three selections will save the data in the top section of each tab: **Tolerance Sensitivities**, **Centered Tolerances**, and **Decentered Tolerances**.
- The **Performance Summary** selection saves a table listing the nominal and "as-built" performance for each field and zoom position.
- The **Compensator Summary** selection saves a table listing the compensator range required for each defined compensator at each field and zoom.

By default, all output selections are checked. Accept all of them or click any unwanted options to deselect them. Click **OK**. A separate Save As dialog box will open for each of the tables you have requested. Each one will be given a generic file name to reflect the type of report (Tolerance_Sensitivities.txt, Centered_Tolerances.txt, etc.). Rename each file as you wish and click **OK**.

You can now open Microsoft Excel (or any spreadsheet program that reads tab-delimited files).

Note: If you are using a version of CODE V that is in a language other than English, the file may be unreadable unless it is opened in a program that can read Unicode format, such as Microsoft Word or Notepad. (English files are saved in ASCII format, while languages other than English are saved in Unicode format.)

In Microsoft Excel, here are some typical things you can do to fit the data on the page:

- widen the columns to see all the data (columns widened within CODE V will print directly from within CODE V, but will need to be widened again when imported to another spreadsheet)
- hide any columns that may not be relevant
- change the orientation to landscape
- print to legal size paper
- change the margins
- change the graphics scaling to less than 100% to fit more on a page

You can then save the data in that format (.xls for Microsoft Excel) for future reference.

Rerunning TOR: Recalculation and Speed of Interactive Tolerancing

If the tolerance sensitivities from the previous run are available and valid, ray tracing is not done, saving considerable computation time. This allows TOR to run faster, whether from the GUI or from the command line. This speed makes interactive tolerancing practical, allowing you to rerun TOR frequently. Changes can be made in tolerance or compensator values and will show their effect quickly when TOR is run again.

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Will cause recalculation (slower):

- The lens is changed in any structural way that has the potential to affect ray tracing (surface data, specifications, apertures, etc.)
- Tolerances or compensators are added or deleted from the set
- Performance measures values are changed (**FRE** and **AZI**, but not **BOR**, **CNS**, or **WTC**)
- A change of ray grid (**NRD**)

Will not cause recalculation (faster):

- All query commands (with "?")
- All immediate commands -see Chapter 24
- Lens title (TIT), designer initials (INI), global coordinates (GLO), material specific gravity (SPG), material price (PRC), first mirror substrate parameters (CUM, THM), TSF (tolerance scale factor) and all tolerance/compensator ***values.***
- All display commands (LIS, SUR, SPC, APE, NSL, PVC, IND, SOL, ZLI, TLI, TTA, CLI, GSC, DRA)
- All quick analyses commands (EVA, FIR, FIO, THO, RSI, SIN, ROF)
- All save/restore operations (SAV, RES - if it has the coefficients, CSA, WRL), except IN lens_name (as the tolerance sensitivity is only saved in the binary .LEN file format).
- Boresight (**BOR**)
- Computational controls (**INV**, **SNS**, **ROU**, but not **NRD**)
- Compensation controls (**WTF**, **WTS**, **SYM**)
- Tolerance limits (**LIM**)
- Output controls (**FUL**, **SEL**, **DST, XYZ**)

In the LDM, the determination of whether a change has been made is based on whether a command is used, not on comparing its value to the prior value; thus, you can delete the coefficients and trigger recalculation when you wish by re-entering the same value on any of the commands which would cause recalculation. In TOR, values are compared and only a change in value can trigger recalculation; since RMS is the default for TOR, **FRE** and **AZI** must be re-entered if the coefficients were originally calculated for them and are to be re-used.

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Description of Output

Sensitivity Tables

The basic sensitivity information for the tolerances is listed for each field and zoom, whether in sensitivity (**SNS**) or inverse sensitivity (**INV**) mode. Each of the tables has a header listing some basic information. The wavelength, weight and number of rays traced for each wavelength are listed. For MTF tolerancing, the number of rays is that which gets through the convolved pupil. This will vary with wavelength, being higher for the shorter wavelengths (since the frequency is a smaller fraction of the cutoff frequency). It is a good check on whether there is any unsuspected clipping of rays. If MTF was requested, the spatial frequency and azimuth for the MTF calculation are listed as well as the diffraction limited value of the MTF (the value if there were no aberrations but using the vignetted pupil as traced). If CEF or PDL was requested, the fiber mode radius as well as the diffraction-limited value of the CEF or PDL (the value if there were no aberrations, only beam clipping) are listed. The value of the RMS, MTF, CEF, or PDL for the system (the nominal value) is listed. For CEF, the value displayed is insertion loss if DB Yes is used.

If full output was selected (**FUL**), a quadratic equation is listed of the form

$$\mathrm{RMS} = \sqrt{A \bullet T^2 + B \bullet T + C}$$

or

$$\mathrm{MTF} = A \bullet T^2 + B \bullet T + C$$

$$\mathrm{CEF} = A \bullet T^2 + B \bullet T + C$$

$$\mathrm{PDL} = A \bullet T^2 + B \bullet T + C$$

This describes the variation of RMS or MTF with tolerance. The value of C is constant for all tolerances at that particular field and zoom and is given below the equation.

Below the header are columns of data describing the tolerances and their effect on RMS, MTF, CEF, or PDL. If compensator groups are used, there will be a separate list for each group. The first two columns, listed under TYPE and CHANGE, describe the tolerance. Both of these columns are under the label, MANUFACTURING ERROR. TYPE is the tolerance type, including the surface number(s), e.g., DLF S3. CHANGE is the value of the tolerance. A 'v' immediately to the right of the value indicates that the tolerance is a variable in inverse sensitivity mode.

The next two columns are listed under the label, CHANGES IN RMS FOR PLUS AND MINUS MANUFACTURING ERRORS (or CHANGES IN MTF... or CHANGES IN CEF... or CHANGES IN PDL...). The first column is the change in RMS, MTF, CEF, or PDL for the value of the tolerance listed under CHANGE. The second column is the change in RMS, MTF, CEF, or PDL for the negative of the value listed under CHANGE. Note that if the tolerance has coupled components, the values are listed only once, next to the description of the last component.

If RMS is being used as the criterion and full output was selected, there will be an additional column to the right of the CHANGES IN RMS. This is the RMS of the change in the wavefront and gives an indication of the size of the aberration which is introduced.

The changes in the compensating parameters, if any, are listed next under the label, COMPENSATING PARAMETERS. If there is more than one compensator and full output was selected, the values are listed one under the other. If full output was not selected and there are three or fewer compensators, the values are listed across the page; if there are more than three, the full output format is used (**FUL** is automatically invoked).

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The value of the compensator is selected to minimize the change in RMS, MTF, CEF, or PDL and is the value associated with the tolerance value listed under CHANGE. Field weights (**WTF**) can be used to influence the minimization process.

If full output was selected, the last two columns, labeled A and B, give values which can be used in the equation for the variation or RMS, MTF, CEF, or PDL given in the header. In the equation, T is a scale factor on the parameter value. When T=1, the equation gives the RMS, MTF or CEF for the value of the tolerance listed under CHANGE. To get the value for the opposite sign of the tolerance, use T=-1; to get the value for twice the value of the tolerance, use T=2.

Zernike Polynomial Coefficients

When Zernike polynomial coefficients are defined, the sensitivity tables include the following information:

- Headings will include the name of the error function as specified with the ERF command.
- In place of the number of rays traced in the listed output, the RMS fit error for the Zernike fit is listed.
- A sensitivity table and summary table of the individual coefficients is provided.
- If there are multiple error functions, a separate table for each error function is listed.

Probable Change

At the end of the columns of data in the sensitivity tables is the probable change in RMS, MTF, CEF, or PDL. This is a statistical value arrived at by assuming a certain distribution for each of the tolerance types. The assumed distribution for one-dimensional tolerances (e.g., fringe, thickness, index, etc.) is uniform. For example, if the change in a thickness is given as 0.001, it is assumed that if many elements were made there is equal probability that the departure from nominal will be anywhere in the range -0.001 to 0.001 and no probability that it will be outside. For cylinder error, the additional assumption is made that the direction of the cylinder is uniformly distributed in 360°. For tilts and decenters, a truncated Gaussian distribution in each component is used. A mean value and spread (1σ) are calculated. The "probable change" in CODE V is defined as the mean plus 2σ meaning that, statistically, 97.7% of the cases will have a smaller change.

If compensators were used, the probable change of compensators is given next, with a separate number being given for each compensator. These numbers give an indication of the range of adjustment which will be required during assembly. Compensators which reach this maximum value are noted.

If compensator groups are being used, the probable changes will be listed at the end of each group. Following the last group, the values for the entire system will be listed.

Distortion Tables

If distortion output was selected (**DST**) or boresight compensation was used (**BOR**), tables for the components of distortion for each zoom position are created. A separate table is created for the x and y components. Only the summary part of the table is created unless **DST** ALL is used. If **DST** ALL is used, for each tolerance the first two columns describe the tolerance and give its value, in the same form as the sensitivity tables. Next to each tolerance are numbers in a row of data labeled A. If there is more than 1 field, a second row labeled B is shown below row A. If there are more than five fields, rows A and B are each continued in additional rows with five fields in the first row and up to four fields in each additional row. The values listed in rows A and B are always in lens units (inches, cm, or mm).

Row A data represent the actual chief ray heights resulting from the tolerance. Row B data are calibrated to a best fit, as described below, and represent the residual distortions at each field after the gross effects of focal length or magnification change, image shift, and image rotation have been removed. Depending on your application, the data in row A or in row B may be of more importance to you.

The first column of data in rows A and B represents the first field in the lens and is labeled BORESIGHT ERROR. If there are two or more fields, the other columns represent these other fields, up to four fields to a row. The boresight error for row A is the actual change in chief ray height for the first field resulting from the

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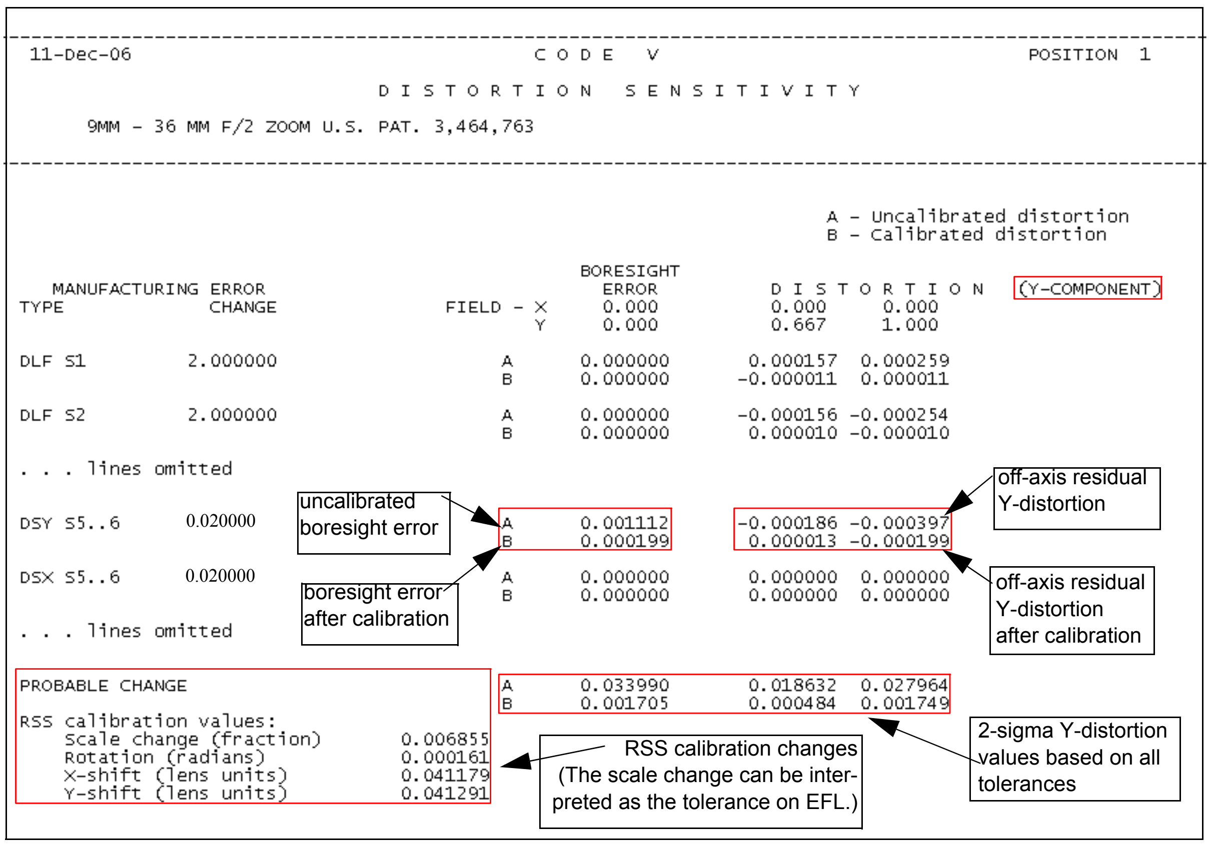
tolerance. The data for the other fields in row A are the changes in chief ray heights for those fields, after subtracting out the boresight error. Thus, they represent the tolerance-induced distortions at each of those fields.

Row B contains calibrated distortion values for each field, including the first field, after the best scale change, image rotation, lateral shift, and user-defined compensation have been removed. Note that after the calibration and compensation are done, there may be a residual boresight error for the first field. This means that after fitting the chief ray heights to a best fit new focal length, image rotation, and image shift, the center of the new image format does not coincide with the first field chief ray height.

At the ends of the columns of data, the probable change of each of the A and B rows is listed. The probable change is defined as the mean plus 2σ, meaning that, statistically, 97.7% of the cases are included. In addition, a summary of the RSS fractional scale change, image rotation, and image shift is listed. The fractional scale change is fractional change in focal length or fractional change in reduction ratio, depending on whether the system is infinite or finite conjugate, respectively. To express the fractional change as a percent change, multiply by 100.



```
 11-Dec-06                                  C O D E   V                               POSITION  1

                                 D I S T O R T I O N   S E N S I T I V I T Y

      9MM - 36 MM F/2 ZOOM U.S. PAT. 3,464,763

                                                                          A - Uncalibrated distortion
                                                                          B - Calibrated distortion

                                                       BORESIGHT
    MANUFACTURING ERROR                                  ERROR       D I S T O R T I O N   (Y-COMPONENT)
 TYPE            CHANGE                     FIELD - X    0.000       0.000     0.000
                                                    Y    0.000       0.667     1.000

 DLF  S1          2.000000                          A    0.000000    0.000157  0.000259
                                                    B    0.000000   -0.000011  0.000011

 DLF  S2          2.000000                          A    0.000000   -0.000156 -0.000254
                                                    B    0.000000    0.000010 -0.000010

 . . . lines omitted

 DSY  S5..6       0.020000                          A    0.001112   -0.000186 -0.000397
                                                    B    0.000199    0.000013 -0.000199

 DSX  S5..6       0.020000                          A    0.000000    0.000000  0.000000
                                                    B    0.000000    0.000000  0.000000

 . . . lines omitted

 PROBABLE CHANGE                                    A    0.033990    0.018632  0.027964
                                                    B    0.001705    0.000484  0.001749
 RSS calibration values:
     Scale change (fraction)          0.006855
     Rotation (radians)               0.000161
     X-shift (lens units)             0.041179
     Y-shift (lens units)             0.041291
```


The information shown in the table is illustrated in Figure 1. Calibration of the distorted FOV includes scale change, rotation, and X and Y shifts to fit the distorted FOV with the smallest residual errors. The original FOV with boresight shift in the illustration maps to row A (X and Y components) in the table. The calibrated FOV maps to row B (X and Y components) in the table.

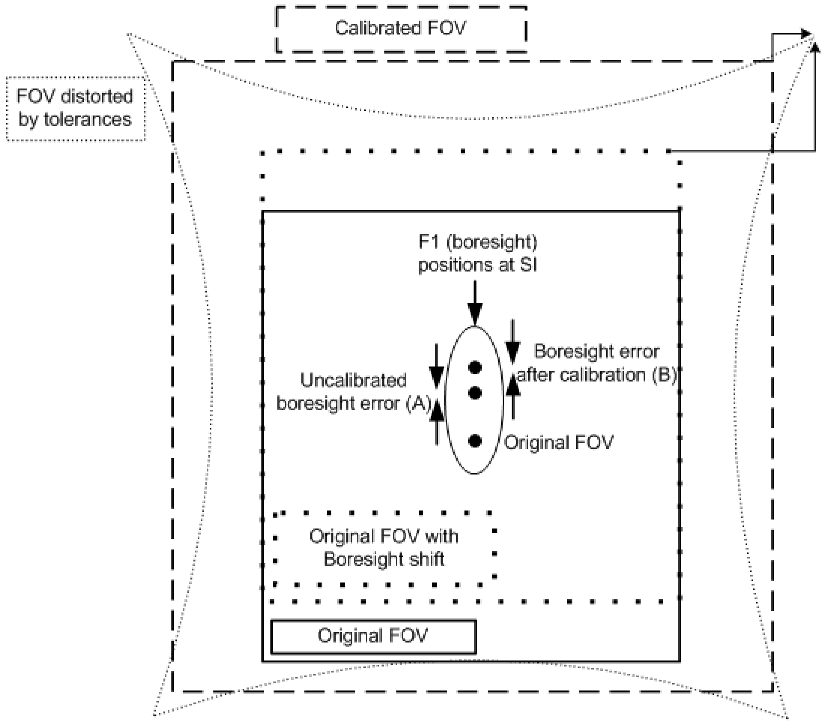


Figure 1. Distortion Effects from Tolerances

Specialized optical systems such as laser scanners and printers often have a scan linearity specification which can take on any of several mathematical forms. The row A data are generally more useful in analyzing the effects of tolerances on scan linearity, but such analysis will generally require post-processing of the TOR output via Macro-PLUS or other programs.

If Zernike coefficients have been defined, and distortion entered into the merit function with the COM DIX or COM DIY commands, this information is included in the distortion table. The units of distortion are specified with the UNI command; the default is lens units.

Tolerance Tables

At the end of an inverse TOR run (INV) are two tables which summarize the centered and decentered tolerances:

- The centered tolerance table lists the surface number, radius, thickness and material for each surface in the lens and lists, where entered, the tolerances on radius, power, irregularity, thickness, index and inhomogeneity.
- The decentered tolerance table lists the lens by element number, along with the front and back radius of each element, and lists tolerances on element wedge, element tilt, element decenter/roll. The wedge and tilt tolerances are given both as an angle, in arc minutes, and as the equivalent total indicator runout (TIR). The decenter/roll tolerances are given as a displacement normal to the optical axis and the equivalent TIR. Note that an element roll is indicated in the table by **(R)** following the value. In the following example output, element 1 is a roll tolerance.

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D E C E N T E R E D
T O L E R A N C E S

Doublet

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. DEC/ROLL(R) TIR	EL. DEC/ROLL(R) mm.
1	61.07222	-42.17543	0.0100	1.0			0.0240	0.0200 (R)
1- 2	61.07222	-316.13853			0.0097	1.0	0.3241	0.5000
2	-42.17543	-316.13853	0.0040	0.4				

For both tables, the limits used to determine the tolerances are summarized. If tolerances have been entered which do not fit the definitions of these two tables, they are listed by name and value in a third table. The tolerance tables can be requested after TOR in the LDM with the TTA command. The tolerances can also be listed in the LDM with the TLI command.

Performance Summary Table

The performance summary table includes the nominal value of the RMS, MTF, CEF, or PDL for each field and the mean plus two sigma value labeled, DESIGN PLUS TOLERANCES. If it is an MTF run, the frequency and azimuth are also included. If CEF or PDL is run, the output fiber mode profile radius is also included. If compensators were used, the mean plus two sigma values of the compensator changes are listed under the label, COMPENSATOR RANGE. If an error function(s) based on Zernike polynomial coefficients is defined, all error functions are listed.

Tolerancing on Other Performance Measures

TOR only tolerances on RMS wavefront error, diffraction MTF at a specified frequency and orientation, fiber coupling efficiency, or polarization dependent loss. You may wish to tolerance on other performance measures, such as encircled energy. A set of macros for finite difference tolerancing or Monte Carlo tolerancing for any user-defined performance measure are provided. Refer to “User-Defined Tolerancing” on page 25D-44 for details of the tolerancing process using these macros.

Table of Reference Sphere Shifts

If calculation of the X, Y, and Z shifts of the center of the optimally compensated, best-fit reference sphere for each tolerance in the lens is requested (**XYZ** command), then a table showing the results is listed (see Figure 2). If **XYZ** Yes is entered, a table is listed that summarizes the probable changes in the X, Y, and Z shifts of the center of the best fit reference sphere. If **XYZ** All is entered, shifts are listed for each tolerance, in addition to the summary listing of the probable changes. The table is output separately for each field and zoom position, immediately following the table of X and Y distortion values, if requested.

Plotted Output

TOR also produces plotted output showing the cumulative probability of the image quality versus the figure of merit, which is either RMS wavefront error, MTF, coupling efficiency, or polarization dependent loss. The results are obtained from a Monte Carlo analysis of the figure of merit wavefront differential equation, which is described by a multidimensional quadratic function of all the tolerances.

Each zoom position is plotted separately, with up to 11 fields on a single plot. If there are more than 11 fields, there will be multiple plots for each zoom position.

You can suppress the plotted output by de-selecting the **Show Plot** checkbox on the **Output Controls** tab (PLO No). See “Defining Output Controls” on page 20-13 for details about the plot output selections.

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Examples

Example 1. TOR using MTF

Start with the triplet. Run TOR at 5 cycles/mm with full output and the distortion table. The MTF will be in the tangential direction (default). Default tolerances and compensators will be used except for the radius tolerances (DLR).

Command inputs:

```
RES  CV_LENS:TRIPLET
DEF  TOL  SA              ! Default tolerances
CMP  DLZ  SI              ! Focal shift compensator
DEL  DLR  SA              ! Delete radius tolerances

TOR                       ! Run TOR, assume default tolerances/compensator
FRE  5                    ! MTF at 5 cycles/mm, tangential orientation
SEL  0.01                 ! Selected output for sensitivity table
FUL                       ! List sensitivity coefficients
DST  ALL                  ! Distortion table with all tolerances listed
GO
```

Output: Sensitivity Table (not all tolerances shown)

```
-------------------------------------------------------------------------------------------
                                       C O D E   V                         POSITION  1

                              I N V E R S E   S E N S I T I V I T Y
                             POLYCHROMATIC MODULATION TRANSFER FUNCTION

            Triplet    U.S. Patent 2,645,157

-------------------------------------------------------------------------------------------


                                                          WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00,  0.00)MAX, (  0.00,   0.00)DEG     656.3 NM      1         796
   FIELD WEIGHT =  1.00                                    587.6 NM      1         796
                                                           486.1 NM      1         804

      FREQUENCY =    5.00 L/MM
      AZIMUTH   =  TANGENTIAL


      DIFFRACTION LIMITED MTF =  0.9909

   Only tolerance sensitivities generating a change in MTF greater than 0.010
   are listed.

      NOMINAL MTF            =  0.7799
                                                                         MTF = A*T**2 + B*T + C

                                                                    (T=SCALE FACTOR FOR CHANGE)

                                                                                C = 0.779893

-------------------------------------------------------------------------------------------

                                                              COMPENSATING PARAMETERS
                                                              ----------------------
                                                                     DLZ S8
   MANUFACTURING ERROR          CHANGES IN MTF FOR
                                  PLUS AND MINUS
  TYPE             CHANGE     MANUFACTURING ERRORS                                   A           B

  BTY S1..2      0.0003000v    -0.0184    0.0198               0.000000     0.000724   -0.019111
  DSY S1..2      0.0200000v    -0.0205    0.0218               0.000000     0.000616   -0.021141
  BTY S3..4      0.0003000v     0.0271   -0.0237               0.000000     0.001703    0.025383
  DSY S3..4      0.0200000v     0.0174   -0.0111               0.000000     0.003193    0.014251

   PROBABLE CHANGE IN MTF       -0.0368
```

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```
          PROBABLE CHANGE OF COMPENSATORS (+/-)                        0.676934

 Units - linear dimensions in mm.    angles in radians,
         fringes in wavelengths at 546.1 nm.

 The probable change and cumulative probability results are based on the
 assumption that the distribution of the MTF converges to a Gaussian form

       CUMULATIVE         CHANGE
      PROBABILITY         IN MTF
       50.0 PCT.          0.0103        * If it is assumed that the errors can
       84.1 PCT.         -0.0133          only take on the extreme values
       97.7 PCT.         -0.0368 *        of the tolerances, the 97.7 percent
       99.9 PCT.         -0.0603          probable change in MTF is  -0.0615
```

Output: Distortion Table (not all tolerances shown)

```
------------------------------------------------------------------------------------------
                                               C O D E   V                     POSITION  1

                                    D I S T O R T I O N   S E N S I T I V I T Y

             Triplet    U.S. Patent 2,645,157

------------------------------------------------------------------------------------------


                                                                        A - Uncalibrated distortion
                                                                        B - Calibrated distortion

                                                         BORESIGHT
      MANUFACTURING ERROR                                  ERROR          D I S T O R T I O N   (Y-COMPONENT)
   TYPE             CHANGE                      FIELD - X  0.000          0.000     0.000
                                                        Y  0.000          0.685     1.000
some lines omitted...

   BTY S6..7       0.000300                         A      0.002234       0.000866  0.002014
                                                    B     -0.001007      -0.000141  0.001007

   BTX S6..7       0.000300                         A      0.000000       0.000000  0.000000
                                                    B      0.000000       0.000000  0.000000

   DSY S6..7       0.020000                         A      0.031625       0.003069  0.006553
                                                    B     -0.003276      -0.000207  0.003276

   DSX S6..7       0.020000                         A      0.000000       0.000000  0.000000
                                                    B      0.000000       0.000000  0.000000


   PROBABLE CHANGE                                  A      0.081035       0.148492  0.221143
                                                    B      0.009597       0.008533  0.012799
   RSS calibration values:
       Scale change (fraction)       0.005211
       Rotation (radians)            0.000084
       X-shift (lens units)          0.072893
       Y-shift (lens units)          0.076259
```

Output: Centered Tolerances

```
------------------------------------------------------------------------------------------
                                                                                   POSITION 1
                                            C E N T E R E D
                                          T O L E R A N C E S

             Triplet    U.S. Patent 2,645,157
 ----------------------------------------------------------------------------------------
                              RADIUS      FRINGES              THICKNESS             INDEX   V-NO   INHOMO-
SUR        RADIUS              TOL        POW/IRR    THICKNESS    TOL      GLASS       TOL    (%)    GENEITY

  1      41.15909                       12.0/ 3.00    6.09756   0.20000   BSM18      0.00050  0.80
```

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2	-957.83146	10.0/ 3.00	9.34958	0.08000			
3	-51.32104	12.0/ 3.00	2.03252	0.06000	PBM22	0.00050	0.80
4	42.37768	8.0/ 3.00	5.99593	0.10000			
5			4.06504	0.10000			
6	247.44562	10.0/ 3.00	6.09756	0.10000	BSM18	0.00100	0.80
7	-40.04016	12.0/ 3.00	85.59343				
8			-0.27339				

Radius, radius tolerance, thickness and thickness tolerance are given in mm.

Fringes of power and irregularity are at 546.1 nm. over the clear aperture

Irregularity is defined as fringes of cylinder power in test plate fit

T O L E R A N C E   L I M I T S

	MINIMUM	MAXIMUM
* RADIUS	0.0200	
* SAG	0.0020	0.0500
** POWER	2.0	12.0
IRREGULARITY	0.50	3.00
THICKNESS	0.02000	0.50000
INDEX	0.00010	0.00200
V-NUMBER(%)	0.20	0.80

* Radius tolerance is determined by both radius and sag limits
** Power tolerance is between 2 and 4 times the irregularity tolerance

Output: Decentered Tolerances

POSITION 1

D E C E N T E R E D
T O L E R A N C E S

Triplet U.S. Patent 2,645,157

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. DEC/ROLL(R) TIR	EL. DEC/ROLL(R) mm.
1	41.15909	-957.83146	0.0060	0.6	0.0098	1.0	0.0169	0.0200
2	-51.32104	42.37768	0.0100	1.3	0.0082	1.0	0.0239	0.0200
3	247.44562	-40.04016	0.0100	1.2	0.0089	1.0	0.0175	0.0200

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smaller of the two clear apertures. For decenter and roll, TIR is a measurement of the induced wedge and is the maximum difference in readings between two indicators, one for each surface, with both surfaces measured at their respective clear apertures. The direction of measurement is parallel to the original optical axis of the element before the perturbation is applied. TIR is measured in mm.

Decenter or roll is measured perpendicular to the optical axis in mm.

T O L E R A N C E   L I M I T S

	MINIMUM	MAXIMUM
TIR	0.0020	0.1000
TILT	0.0003	0.0050
DECENTER	0.0200	0.5000
ROLL	0.0200	0.5000

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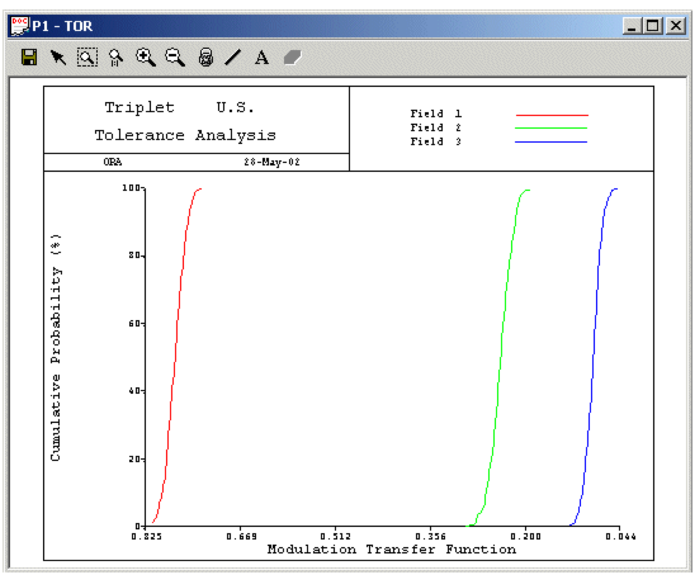
Output: Performance Summary

```
-----------------------------------------------------------------------------------------------------
                                                                                          POSITION 1

                                    P E R F O R M A N C E   S U M M A R Y
                                 POLYCHROMATIC MODULATION TRANSFER FUNCTION


              Triplet    U.S. Patent 2,645,157

 ----------------------------------------------------------------------------------------------------

                                                                           WAVELENGTH   WEIGHT
                                                                            656.3 NM       1
                                                                            587.6 NM       1
                                                                            486.1 NM       1

 ----------------------------------------------------------------------------------------------------

   RELATIVE   FREQ    AZIM   WEIGHT    DESIGN  DESIGN  COMPENSATOR RANGE (+/-) *
     FIELD    L/MM    DEG                      + TOL *
                                                          DLZ S8

 0.00, 0.00    5.00   TAN   1.00      0.782   0.737    0.691198
 0.00, 0.69    5.00   TAN   1.00      0.234   0.195    0.691198
 0.00, 1.00    5.00   TAN   1.00      0.091   0.060    0.691198

 ----------------------------------------------------------------------------------------------------

               * The change in MTF is a mean plus 2 Sigma value (97.7 percent)
                 and assumes a uniform distribution of manufacturing errors over the range
                 for all tolerances except decentration errors which have a truncated
                 Gaussian distribution in X and Y

                 The compensator range is a mean plus 2 Sigma value.
                 Linear compensators are in units of millimeters.
                 Angular compensators are in radians.
```

Output: Plot



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Example 2. Table of reference sphere shifts generated using XYZ command.

```
Command inputs:
   RES  CV_LENS:DBGAUSS
   YAN 0                        !
   DEL  SOL  SA                 ! Delete solves
   DLT S1                       ! Tolerance on thickness
   CMP DLT SI                   ! Thickness compensator

   TOR                          ! Run TOR, assume default tolerances/compensator
   XYZ ALL                      ! Reference sphere table with all tolerances listed
   GO
```

```
-------------------------------------------------------------------------------
   25-Jul-00                           C O D E   V                    POSITION  1

                C H A N G E   I N   C E N T E R   O F   R E F E R E N C E   S P H E R E

         Double Gauss - U.S. Patent 2,532,751

-------------------------------------------------------------------------------


     MANUFACTURING ERROR                         CHANGE IN CENTER OF REFERENCE SPHERE
   TYPE               CHANGE               FIELD - X      0.000
                                                   Y      0.000

   DLT S1          0.400000                     X       0.000000
                                                Y       0.000000
                                                Z      -0.001800



   PROBABLE CHANGE                              X       0.000000
                                                Y       0.000000
                                                Z       0.002079

--------------------------------------------------------------------------------
```

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Example 3. TOR using Polarization Dependent Loss (PDL) Tolerancing

```
Command inputs:
  RES  CV_LENS:OPTISO
  DLA S4 F .001          ! Alpha tilt tolerance on surface 4
  TOR                    ! Run TOR
  MPR PDL .0052          ! Activate PDL tolerancing with fiber mode radius
                         ! of .0052
  PLO N                  ! Suppress the culmative probability curves
  DB                     ! Convert PDL to decibels
```

Output: Changes in PDL

```
                      I N V E R S E   S E N S I T I V I T Y
                         POLARIZATION DEPENDENT LOSS (dB)

         Optical isolator - forward path - U.S. Pat. 5,208,876, Pan, E-tek

---------------------------------------------------------------------------------------------------------

                                                                      WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.74)DEG     1300.0 NM       1         860
   FIELD WEIGHT =  1.00

      FIBER MODE RADIUS =  0.005200 mm

      DIFFRACTION LIMITED PDL =  0.0000
      NOMINAL PDL             = -0.0371

---------------------------------------------------------------------------------------------------------
   MANUFACTURING ERROR          CHANGES IN PDL FOR
                                  PLUS AND MINUS
  TYPE              CHANGE      MANUFACTURING ERRORS

  DLA S4          0.0010000       0.0344   -0.0484

   PROBABLE CHANGE IN PDL       -0.0505

   Units - linear dimensions in mm.    angles in radians,
           fringes in wavelengths at 546.1 nm.

   The probable change and cumulative probability results are based on the
   assumption that the distribution of the PDL converges to a Gaussian form

         CUMULATIVE         CHANGE
        PROBABILITY         IN PDL
         50.0 PCT.         -0.0023        * If it is assumed that the errors can
         84.1 PCT.         -0.0263          only take on the extreme values
         97.7 PCT.         -0.0505 *        of the tolerances, the 97.7 percent
         99.9 PCT.         -0.0748          probable change in PDL is  -0.0904
```

Output: Performance Summary

```
                     P E R F O R M A N C E   S U M M A R Y
                        POLARIZATION DEPENDENT LOSS (dB)

         Optical isolator - forward path - U.S. Pat. 5,208,876, Pan, E-tek

---------------------------------------------------------------------------------------------------------

                                                                      WAVELENGTH   WEIGHT
                                                                      1300.0 NM       1
---------------------------------------------------------------------------------------------------------


   RELATIVE    FIBER MODE    WEIGHT   DESIGN   DESIGN
     FIELD     RADIUS (mm)                      + TOL   *

 0.00, 0.00    0.005200      1.00    -0.0371 -0.0876

---------------------------------------------------------------------------------------------------------

               * The probable change and cumulative probability results are based on the
                 assumption that the distribution of the PDL converges to a Gaussian form
```

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Example 4. Zernike error functions in TOR

When Zernike polynomials (see “Zernike Polynomials” on page C-1) are used in TOR, the wavefronts are fit to the specified polynomial and the wavefront differentials are obtained in terms of the same polynomials. Since Zernike polynomials are defined in a circle, this type of error function is best used when the pupils are circular and unobstructed.

The command input for a simple example is shown below. The wavefronts are fit to a 15-term standard Zernike polynomial on the exit sphere. In this case, the error function contains all 15 terms, and is a weighted sum of squares of the coefficients. The default weights are those that result in the variance of the wavefront. In the TOR output, the RMS wavefront error (square root of the variance) is reported; this is similar to the standard RMS wavefront error function in TOR.

Command input: A simple example of a Zernike error function

```
res cv_lens:singlet
tor
zrn 15     ! Defines a 15 term standard Zernike
           ! on the exit sphere
go
```

The sensitivity table for the one field in this lens is shown below. This looks almost the same as the table for the standard RMS error function, since the same quantity is being calculated (although with Zernike polynomials instead of ray grids), and the numbers are very similar. Differences include the name of the error function (E1 - RMS Wavefront Error) and the RMS FIT ERROR in place of the number of rays.

Output: Sensitivity table for the Zernike error function

```
                                    I N V E R S E   S E N S I T I V I T Y
                                           E1 - RMS Wavefront Error

       Singlet

-----------------------------------------------------------------------------------------

                                                       WAVELENGTH  WEIGHT  RMS FIT ERROR
    FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG  500.0 NM       1      0.0018
    FIELD WEIGHT =  1.00

       NOMINAL E1             =  1.7152

-----------------------------------------------------------------------------------------
    MANUFACTURING ERROR            CHANGES IN E1 FOR        COMPENSATING PARAMETERS
                                     PLUS AND MINUS
   TYPE             CHANGE       MANUFACTURING ERRORS        DLZ S3

   DLF S1        12.0000000v      0.0000     0.0000         -0.339481
   DLF S2        12.0000000v      0.0000     0.0000          0.332384
   DLR S1         2.5000000v      0.0002     0.0002          5.180385
   DLR S2        0.2400E+03v      0.0000     0.0000         -0.831907
   DLT S1         0.5000000v      0.0000     0.0000         -0.356744
   DLN S1         0.0020000v      0.0000     0.0000         -0.372490
   CYD S1         3.0000000v      0.0088     0.0088         -0.041075
   CYD S2         3.0000000v      0.0088     0.0088          0.041546
   CYN S1         3.0000000v      0.0088     0.0088         -0.041075
   CYN S2         3.0000000v      0.0088     0.0088          0.041546
   TRY S1         0.1000000v      0.0014     0.0014          0.000000
   TRX S1         0.1000000v      0.0014     0.0014          0.000000
   BTY S1..2      0.0050000v      0.0002     0.0002          0.000000
   BTX S1..2      0.0050000v      0.0002     0.0002          0.000000
   DSY S1..2      0.5000000v      0.0055     0.0055          0.000000
   DSX S1..2      0.5000000v      0.0055     0.0055          0.000000

    PROBABLE CHANGE IN E1         0.0262

             PROBABLE CHANGE OF COMPENSATORS (+/-)          6.112863
```

At the end of the TOR listing, the definition of the error function is listed. See the following output example. The weight for the error function (1.0) is shown, and the weight for each Zernike terms is shown next to the coefficient number. In this case, these are the default weights.

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Output: Definition of Zernike error function

```
                Zernike Polynomial Error Function Definition
                     Standard Zernike ( 15 terms)
                     Fit to exit sphere


 E1    RMS Wavefront Error                                        1.000000
            C1       1.000000
            C2       0.250000
            C3       0.250000
            C4       0.166667
            C5       0.333333
            C6       0.166667
            C7       0.125000
            C8       0.125000
            C9       0.125000
            C10      0.125000
            C11      0.100000
            C12      0.100000
            C13      0.200000
            C14      0.100000
            C15      0.100000
```

The LIS SEN command will list the changes in each of the Zernike coefficients for each tolerance. The output for the first tolerance is shown below.

Output: Changes in Zernike coefficients for the first tolerance

```
  MANUFACTURING ERROR          CHANGES IN E1 FOR        COMPENSATING PARAMETERS
                                 PLUS AND MINUS
 TYPE             CHANGE      MANUFACTURING ERRORS        DLZ S3

 DLF S1        12.0000000v      0.0000     0.0000        -0.339481
                    Z1          0.0000     0.0000
                    Z2          0.0000     0.0000
                    Z3          0.0000     0.0000
                    Z4          0.0000     0.0000
                    Z5          0.0004    -0.0004
                    Z6          0.0000     0.0000
                    Z7          0.0000     0.0000
                    Z8          0.0000     0.0000
                    Z9          0.0000     0.0000
                    Z10         0.0000     0.0000
                    Z11         0.0000     0.0000
                    Z12         0.0000     0.0000
                    Z13        -0.0016     0.0016
                    Z14         0.0000     0.0000
                    Z15         0.0000     0.0000
```

The input for a more complicated Fringe Zernike error function is shown below. In this case, there are three error functions, with each one using a subset of the Zernike coefficients. The first error function (E1) is a combination of c4 and c9, and represents spherical aberration. The second (E2) includes the two primary coma terms and the third (E3) includes the two primary astigmatism terms. The spherical aberration error function is weighted heavier than the other two. This affects the compensation. The TOR output includes a sensitivity table for each error function.

Command input: Three Zernike error functions

```
res cv_lens:singlet
tor
zfr enp 37        ! Defines a 37 term Fringe Zernike
                  ! on the entrance pupil
erf e1 "Spherical aberration" 1.0
com e1 c4
com e1 c9
erf e2 "Coma" 0.5
com e2 c7
com e2 c8
erf e3 "Astigmatism" 0.5
com e3 c5
com e3 c6
go
```

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Example 5. Vertical critical dimension

Using a perfect, single focus, 0.5 NA, λ = 500 nm system and a Surface Z-Displacement (DLZ) tolerance, these are some examples of TOR input using the lithographic error functions, and examples of the resulting output.

```
LEN
TIT "Perfect lens, finite object, NA = .5, WL = 500, on-axis"
SO 0 10
S 0 -5
CIR 5.775
S 0 0
S 0 -5
STO
WL 500
NAO .5
CA APE
GO
POL N
FFO 0.000
IFO 0.000
NFO 1

DLZ SI .0001

TOR
PLO N
SNS
BAR 1 .0005
UNI MIC
RNA .75
CDT .6
GO
```

The TOR output follows.

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```
                                   C O D E   V                        POSITION  1

                                 S E N S I T I V I T Y   A N A L Y S I S
                                     E1 - Vertical Critical Dimension

           Perfect lens, finite object, NA = .5, WL = 500, on-axis
 ----------------------------------------------------------------------------------
                                                     WAVELENGTH   WEIGHT   NO. OF RAYS
    FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.00)DEG     500.0 NM      1       3209
     FIELD WEIGHT =  1.00

        NUMBER OF BARS    =    1
        BAR WIDTH         =  0.000500 in
        AZIMUTH           =    0.00 degrees
        PUPIL FILL        =  0.750
        THRESHOLD         =  0.600

        DIFFRACTION LIMITED E1 = 12.3793 MIC
        NOMINAL E1             = 12.3793 MIC
 ----------------------------------------------------------------------------------
     MANUFACTURING ERROR          CHANGES IN CD FOR
                                    PLUS AND MINUS
    TYPE             CHANGE      MANUFACTURING ERRORS

    DLZ S4         0.0001000v     -0.0938   -0.0938

     PROBABLE CHANGE IN E1        0.0247

     Units - linear dimensions in inches angles in radians,
             fringes in wavelengths at 546.1 nm.

     The probable change and cumulative probability results are based on the
     assumption that the distribution of the E1 converges to a Gaussian form

           CUMULATIVE        CHANGE
          PROBABILITY        IN E1
           50.0 PCT.        -0.0313        * If it is assumed that the errors can
           84.1 PCT.        -0.0033          only take on the extreme values
           97.7 PCT.         0.0247 *        of the tolerances, the 97.7 percent
           99.9 PCT.         0.0526          probable change in E1 is  -0.0938

 ----------------------------------------------------------------------------------
                                                                      POSITION  1
                              P E R F O R M A N C E   S U M M A R Y
                                 E1 - Vertical Critical Dimension

             Perfect lens, finite object, NA = .5, WL = 500, on-axis

 ----------------------------------------------------------------------------------

                                                                WAVELENGTH   WEIGHT
                                                                   500.0 NM       1


 ----------------------------------------------------------------------------------

                    RELATIVE     WEIGHT   DESIGN   DESIGN
                      FIELD                        + TOL   *

      0.00, 0.00    0.000000     1.00    12.3793 12.4040

 ----------------------------------------------------------------------------------

                    * The probable change and cumulative probability results are based
 on the
                    assumption that the distribution of the E1  converges to a Gaussian
 form
```

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Example 6. Horizontal and vertical critical dimension combined in one error function

Using the same lens specification and DLZ tolerance as in Example 5, the following TOR commands can be used to combine the horizontal and vertical critical dimension in one error function.

```
TOR
PLO N
SNS
BAR 1 .0005
UNI MIC
RNA .75
CDT .6
ERF E1 'Horizontal & Vertical CD combined'
COM E1 CDV 0.5
COM E1 CDH 0.5
GO
```

The TOR output follows.

```
                                   C O D E   V                          POSITION  1

                                 S E N S I T I V I T Y   A N A L Y S I S
                                  E1 - Horizontal & Vertical CD combined

         Perfect lens, finite object, NA = .5, WL = 500, on-axis
------------------------------------------------------------------------------------
                                                WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.00)DEG     500.0 NM      1       3209
    FIELD WEIGHT =   1.00

       NUMBER OF BARS    =    1
       BAR WIDTH         =  0.000500 in
       AZIMUTH           =    0.00 degrees
       PUPIL FILL        =  0.750
       THRESHOLD         =  0.600

       DIFFRACTION LIMITED E1 = 12.3793 MIC
       NOMINAL E1             = 12.3793 MIC
------------------------------------------------------------------------------------
    MANUFACTURING ERROR          CHANGES IN CD FOR
                                  PLUS AND MINUS
   TYPE              CHANGE      MANUFACTURING ERRORS

   DLZ S4         0.0001000v     -0.0938   -0.0938

    PROBABLE CHANGE IN E1        0.0247

    Units - linear dimensions in inches angles in radians,
            fringes in wavelengths at 546.1 nm.

    The probable change and cumulative probability results are based on the
    assumption that the distribution of the E1 converges to a Gaussian form

          CUMULATIVE         CHANGE
         PROBABILITY          IN E1
          50.0 PCT.         -0.0313        * If it is assumed that the errors can
          84.1 PCT.         -0.0033          only take on the extreme values
          97.7 PCT.          0.0247 *        of the tolerances, the 97.7 percent
          99.9 PCT.          0.0526          probable change in E1 is  -0.0938
```

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```
 ---------------------------------------------------------------------------------
                                                                       POSITION  1

                                P E R F O R M A N C E   S U M M A R Y
                                E1 - Horizontal & Vertical CD combined

                    Perfect lens, finite object, NA = .5, WL = 500, on-axis

---------------------------------------------------------------------------------
                                                              WAVELENGTH   WEIGHT
                                                                 500.0 NM      1

---------------------------------------------------------------------------------

                   RELATIVE     WEIGHT   DESIGN  DESIGN
                    FIELD                         + TOL  *

     0.00, 0.00    0.000000     1.00   12.3793 12.4040

---------------------------------------------------------------------------------

                * The probable change and cumulative probability results are based on the
                 assumption that the distribution of the E1  converges to a Gaussian form
```

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Example 7. Horizontal and vertical critical dimension calculated separately

Using the same lens specification and DLZ tolerance as in Example 5, the following TOR commands can be used to calculate the horizontal and vertical critical dimension error functions separately.

```
TOR
PLO N
SNS
BAR 1 .0005
UNI MIC
RNA .75
CDT .6
ERF E1 'Vertical CD'
COM E1 CDV
ERF E2 'Horizontal CD'
COM E2 CDH
GO
```

The TOR output follows.

```
                                      C O D E   V                          POSITION  1

                                    S E N S I T I V I T Y   A N A L Y S I S
                                                E1 - Vertical CD

         Perfect lens, finite object, NA = .5, WL = 500, on-axis
-----------------------------------------------------------------------------------

                                                   WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.00)DEG     500.0 NM      1       3209
    FIELD WEIGHT =  1.00

       NUMBER OF BARS   =    1
       BAR WIDTH        =  0.000500 in
       AZIMUTH          =    0.00 degrees
       PUPIL FILL       =  0.750
       THRESHOLD        =  0.600

       DIFFRACTION LIMITED E1 = 12.3793 MIC
       NOMINAL E1             = 12.3793 MIC
-----------------------------------------------------------------------------------
    MANUFACTURING ERROR          CHANGES IN CD FOR
                                   PLUS AND MINUS
   TYPE             CHANGE      MANUFACTURING ERRORS

   DLZ S4         0.0001000v     -0.0938   -0.0938

    PROBABLE CHANGE IN E1        0.0247

    Units - linear dimensions in inches angles in radians,
            fringes in wavelengths at 546.1 nm.

    The probable change and cumulative probability results are based on the
    assumption that the distribution of the E1 converges to a Gaussian form

          CUMULATIVE        CHANGE
         PROBABILITY        IN E1
          50.0 PCT.        -0.0313        * If it is assumed that the errors can
          84.1 PCT.        -0.0033          only take on the extreme values
          97.7 PCT.         0.0247 *        of the tolerances, the 97.7 percent
          99.9 PCT.         0.0526          probable change in E1 is  -0.0938

-----------------------------------------------------------------------------------
                                      C O D E   V                          POSITION  1

                                    S E N S I T I V I T Y   A N A L Y S I S
                                               E2 - Horizontal CD

         Perfect lens, finite object, NA = .5, WL = 500, on-axis
-----------------------------------------------------------------------------------

                                                   WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,  0.00)DEG     500.0 NM      1       3209
    FIELD WEIGHT =  1.00
```

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```
        NUMBER OF BARS   =    1
        BAR WIDTH        =  0.000500 in
        AZIMUTH          =    0.00 degrees
        PUPIL FILL       =  0.750
        THRESHOLD        =  0.600


        DIFFRACTION LIMITED E2 = 12.3793 MIC
        NOMINAL E2             = 12.3793 MIC

 ---------------------------------------------------------------------------------
     MANUFACTURING ERROR          CHANGES IN CD FOR
                                    PLUS AND MINUS
    TYPE             CHANGE      MANUFACTURING ERRORS

    DLZ S4         0.0001000v     -0.0938   -0.0938

     PROBABLE CHANGE IN E2        0.0247

     Units - linear dimensions in inches angles in radians,
             fringes in wavelengths at 546.1 nm.

     The probable change and cumulative probability results are based on the
     assumption that the distribution of the E2 converges to a Gaussian form

           CUMULATIVE        CHANGE
          PROBABILITY        IN E2
           50.0 PCT.        -0.0313       * If it is assumed that the errors can
           84.1 PCT.        -0.0033         only take on the extreme values
           97.7 PCT.         0.0247 *       of the tolerances, the 97.7 percent
           99.9 PCT.         0.0526         probable change in E2 is  -0.0938
 ---------------------------------------------------------------------------------
                                                                        POSITION  1

                                   P E R F O R M A N C E   S U M M A R Y
                                             E1 - Vertical CD

              Perfect lens, finite object, NA = .5, WL = 500, on-axis

----------------------------------------------------------------------------------
                                                                   WAVELENGTH   WEIGHT
                                                                      500.0 NM       1

----------------------------------------------------------------------------------
                  RELATIVE     WEIGHT   DESIGN  DESIGN
                    FIELD                       + TOL  *

     0.00, 0.00    0.000000     1.00   12.3793 12.4040

----------------------------------------------------------------------------------
                    * The probable change and cumulative probability results are
                      based on the assumption that the distribution of the E1
                      converges to a Gaussian form

                                                                        POSITION  1

                                   P E R F O R M A N C E   S U M M A R Y
                                            E2 - Horizontal CD

              Perfect lens, finite object, NA = .5, WL = 500, on-axis

----------------------------------------------------------------------------------
                                                                   WAVELENGTH   WEIGHT
                                                                      500.0 NM       1

----------------------------------------------------------------------------------

                  RELATIVE     WEIGHT   DESIGN  DESIGN
                    FIELD                       + TOL  *

     0.00, 0.00    0.000000     1.00   12.3793 12.4040

----------------------------------------------------------------------------------
                    * The probable change and cumulative probability results are based
                      on the assumption that the distribution of the E2 converges to
                      a Gaussian form
```

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Technical Notes

Background

The TOR option is a tolerancing procedure based on real ray tracing that predicts the effect of the various tolerances on RMS wavefront error, diffraction MTF, fiber coupling efficiency (CEF), or polarization dependent loss (PDL). It is based on a wavefront differential ray trace[1,2] that provides the derivative of the OPD with respect to the tolerances. This provides an extremely efficient way to calculate the changes in RMS wavefront error, MTF, CEF, or PDL [2,3,4] used in the statistical calculations[5] (see "References" on page 20-71).

For details about the formula used in CODE V for polychromatic RMS, go to "Polychromatic RMS" on page 19-414.

Use of Differentials vs. Finite Differences vs. Monte Carlo

The differentials calculated by TOR are exact derivatives. If the OPD for a ray is plotted versus the value of a parameter, the slope of the function at the nominal value of the parameter is the derivative calculated by TOR. Thus, TOR assumes that the OPD varies linearly with the tolerance. This is a good assumption for tolerancing applications where the changes are very small and the performance of the lens varies only slightly from its design value. When this linear model is used in the calculation of the wavefront variance, a quadratic function results, since the variance is the sum of squares of the OPD values (the RMS is the square root of the variance). A similar process occurs for the MTF, CEF, and PDL calculations. Thus, TOR predicts the quadratic variation of the figure of merit (RMS wavefront error, MTF, CEF, or PDL).

The calculation of the differentials is very fast since the system needs to be traced only once and very little additional computations are needed over the basic ray trace. Thus, there is no need to change the system and re-evaluate it in order to determine the effects of a change. This results in significant time savings over a finite difference approach. For example, for a 12 surface Double Gauss lens which might require 100 separate tolerances, the TOR approach using differentials would be about 200 times faster than a finite difference approach.

For a Monte Carlo analysis, the system must be traced once for every trial. For accurate results, 100 to 1,000 trials are typical. This means the TOR approach would be approximately 100 times to 1,000 times faster.

Inverse Sensitivity

TOR operates in either sensitivity mode (SNS) or inverse sensitivity mode (INV). For SNS, the changes in performance are calculated for the given values of the tolerance. For INV, the values of the tolerances are adjusted to produce a specific degradation in the performance, for example, a drop of 0.01 in the MTF or CEF or an increase of 0.01 in RMS wavefront error. This specified performance degradation may be exceeded or may not be reached for a specific tolerance, depending on that tolerance's effects and its limits. The determination of the tolerance value takes account of the quadratic variation of the performance. Since the degradation for a positive tolerance may be different than the degradation for a negative tolerance, the worse case is used. After TOR calculates the value of a tolerance that achieves the specified performance degradation, the maximum and minimum limits on the tolerance may limit the value. Thus, it is possible for a tolerance to be at its minimum value with the degradation exceeding the specified value, or if the tolerance is very insensitive it will be set at its maximum value with very little degradation in the performance.

Limitations of the Linear Model

Because TOR uses a linear model for the change in OPD, it is appropriate only when the tolerance changes cause a small change in performance (after compensation). However, this is precisely the situation hoped for when calculating tolerances; the changes should be small enough so that the degradation is small.

The linear model of OPD with respect to tolerance value can sometimes give surprising results. For example, consider a spherical mirror with both the object and image at the center of curvature. This system has a very low sensitivity to decenter of the mirror. This is because the system is well corrected and there is no axial

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coma when a small decenter or tilt is applied to the mirror. A graph of wavefront variance versus mirror decenter would show a quartic (fourth order) variation; there is no quadratic effect because of the lack of axial coma. Thus, TOR would predict zero sensitivity for a decenter of the mirror (no quadratic effect on performance). In this case, the decenter of the mirror is one of the least sensitive tolerances. In a full tolerance analysis, all of the manufacturing and assembly defects must be considered. In general, there will only be a few which are significant and which will require tightening. These "drivers" are the ones which will determine the final performance of the system. Insensitive tolerances, such as the mirror decenter, can generally be set to their maximum allowed values. TOR allows you to differentiate between the drivers and the insensitive tolerances so that a cost effective result can be obtained.

In some cases, you may want to know how your system performance varies for a very large value of a specific tolerance, without needing a statistical analysis using many tolerances. In this case, TOR may not be the most appropriate tool to use. Re-evaluating the system manually after changing a variable may give you what you want more directly and with better accuracy; remember to check both + and - changes, unless you know it is symmetric. Use the TSF CHA command to quickly model a tolerance perturbation (see page 8-27 for details about TSF CHA).

Technical Approach

The calculations are based on a differential ray trace which provides the derivatives of the wave aberration with respect to each of the perturbations[2,3,4,5] (see "References" on page 20-71). Grids of rays are traced through the lens as needed. For each ray, the wave aberration derivatives are calculated for each perturbation, and each pair of perturbations, and appropriately summed. The final result is a set of coefficients defining a function which describes the variation of RMS, MTF, CEF, or PDL with respect to each of the parameters of interest (perturbations). Since each pair of perturbations is also considered, the overall performance prediction for TOR includes cross-terms (the performance impact to interactions between tolerances). This means that, for small tolerances, the performance prediction accuracy of TOR is equivalent to a Monte Carlo simulation with a large number of trials; however, TOR is much faster. The function is basically a Taylor series expansion about the nominal (unperturbed) system so that it is most accurate for small departures from the nominal system. The RMS calculation is equivalent in accuracy to the WAVE option and the MTF or CEF values are equivalent in accuracy to the MTF or CEF option (including diffraction effects). Because of the formulation of both computations. the accuracy of the predicted computation does not depend on the lens system being near diffraction limited.

The variation of the MTF, CEF, PDL, or square of the RMS (variance of the wavefront aberration) is, in general, approximately quadratic with respect to a lens parameter for small changes about the nominal value of the parameter. An equation describing this variation would have both a quadratic and linear term. If the linear term were non-zero, the system could improve when the parameter is moved in one direction, while degrading in the other direction. An example is shown in Figure 2.

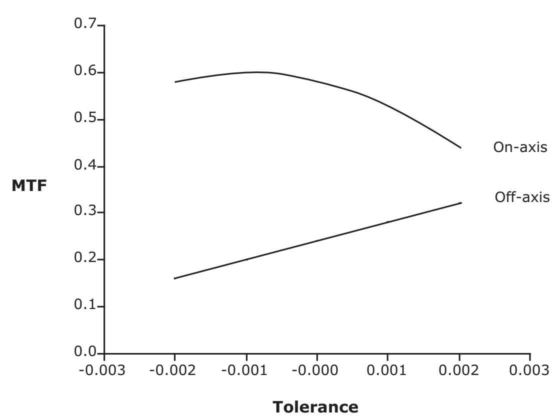

Figure 2. MTF vs. tolerance

You, the designer, usually submit for tolerancing a lens that you expect to be optimum. You are therefore unprepared to see RMS or MTF values improve as a result of tolerance changes. The explanation is that, although the lens is an optimized balance for **all** fields, zoom positions and MTF azimuths, any single field

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angle (or azimuth for MTF) in any zoom position will not, in general, be separately optimum. Thus, a given tolerance can, in fact, enhance the performance for one image point (and azimuth) but presumably degrade other image points even more. In addition, the original design was subjected to constraints which are not imposed in tolerancing (EFL, image distance, etc.). Thus, conceivably there may be tolerances that will enhance performance at **every** field point since the lens is unrestricted by constraints.

The changes in MTF which are calculated depend on the focal position, thus making it possible to have widely differing sensitivities to a particular perturbation at two different focal settings. When using TOR, the lens should be at its best focus position.

Cylinder Tolerances (Irregularity)

The aberration introduced by CYN and CYD is represented by cylindrical power in one meridian, and thus includes average power as well as astigmatism. Thus, it is important to have a compensating parameter which compensates focus when using these.

Inhomogeneity

The inhomogeneity model in TOR is a combination of a linear radial index gradient and a quadratic radial gradient. The equation is

$$N = (8.6)(HOM)(p/R)[1 - 0.8(p/R)]$$

where

N	=	Change in index of refraction
HOM	=	Tolerance value
p	=	Radial distance from center of element
R	=	Semi-diameter of element (average of the two semi-diameters)

The peak-to-peak of this function is ~(2.7)(HOM). If a focus compensator is included, it may be affected by this model, depending on where the beam falls on the element.

Statistical Models

In the statistical summary given in TOR, certain assumptions are made about the distribution of manufacturing errors. For one-dimensional tolerances (e.g., radius, thickness, index, homogeneity, etc., it is assumed that the error is equally likely to be anywhere within the tolerance range. This is called a uniform model for the probability density function.

In the case of cylindrical irregularity, which may have arbitrary orientation, it is assumed that the manufacturing error can be anywhere with equal probability within a cylinder whose radius is equal to the magnitude of the input perturbation. It is convenient in this case to transform coordinates into a polar form in order to integrate out the angular dependence. When this is done, the resulting probability density function for the radial coordinate is triangular as illustrated in Figure 3. The implication of this form is that the errors tend to accumulate near their maximum magnitude, which is probably a reasonable model for irregularity.

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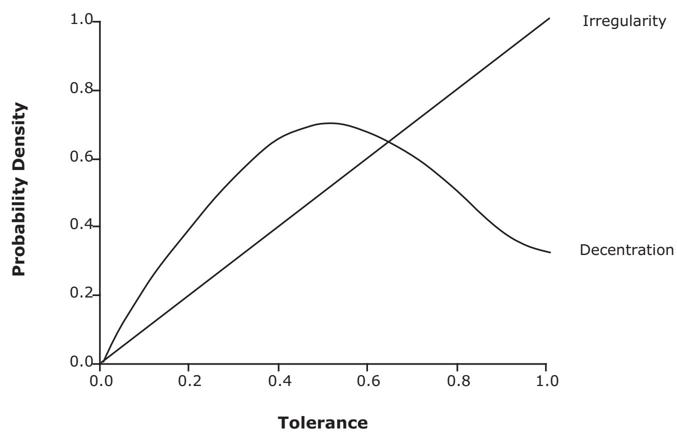

Figure 3. Probability density vs. tolerance

For decentration errors (e.g., tilt, decenter, roll, etc.), it is assumed that each component has a Gaussian probability density function truncated at the $1/e^2$ point. The resulting radial distribution has a truncated Rayleigh form. This is shown as the second curve in Figure 2. The maximum is halfway between the center and edge. This is a more reasonable model for decentration errors which do not tend to accumulate near the maximum value.

In order for these two-dimensional distributions to be used, both components of irregularity and decentration must be entered and each must have the same tolerance. For example, for a surface tilt enter both DLA and DLB (or use TIL, which enters both components).

Lateral Alignment

TOR assumes that lateral displacements are relative to a stationary mechanical axis and can assume values randomly in any direction. If the assembly procedure uses one optical component (e.g., a primary mirror) to establish a centerline, then no decenter tolerance should be entered on that component. The tolerances on the others then describe the lateral alignment capability.

Compensator Labels

Compensator labels allow the user to enter different compensators for different sets of tolerances (through labeling tolerances and compensators), all in the same TOR run. This may be used, for example, on a relay system, consisting of two sub-assemblies, each of which is built and assembled separately. Let's say that the first sub-assembly is surfaces 1 through 10 and the compensator used to align it is the axial shift of the element defined by surfaces 5 and 6. The second sub-assembly is surfaces 11-20 and its compensator is the axial shift of the element defined by surfaces 13 and 14. In addition, when the whole system is put together, the back focus is used as a compensator. The tolerances and compensators for this case would be entered as follows.

```
DEF  TOL  S1..10  L'A'       ! Default tolerances on surfaces 1 to 10, group A
CMP  DSZ  S5..6  L'A'        ! Compensators
CMP  DLZ  SI  L'A'           ! for group A
DEF  TOL  S11..20  L'B'      ! Default tolerances on surfaces 11 to 20, group B
CMP  DSZ  S13..14  L'B'      ! Compensators
CMP  DLZ  SI  L'B'           ! for group B
```

Note that the compensator, DLZ SI, is used in both groups. The advantage of using compensator groups over doing two separate TOR runs is that the cross terms between the two groups are included in the statistical summaries, thus giving an accurate simulation.

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Combining Results of Two or More TOR Analyses

Occasionally, it may be necessary to combine the results of two different tolerance analyses of the same system and obtain the probable change in MTF, RMS, CEF, or PDL for the combination, although the recommended way is to use compensator groups. The mean (M) and standard deviation (S) for the combination are determined from the individual means and standard deviations from the two separate runs and combined as follows:

$$M = M_1 + M_2$$

$$S = \sqrt{S_1^2 + S_2^2}$$

where the subscripts refer to the two separate runs. It should be noted that this will give a less accurate result than one large run because the cross-terms between the two runs are missing and, therefore, the single large run is recommended.

The calculation of the mean and standard deviation for the individual runs and the resulting probable change for the combination is different for MTF, CEF, PDL, and RMS.

For MTF, CEF, or PDL:

$$M_1 = C_1(50.0)$$

$$S_1 = C_1(50.0) - C_1(84.1)$$

where $C_1(50.0)$ and $C_1(84.1)$ are the changes at the 50.0 and 84.1 percent cumulative probability, respectively, for the first run. Identical calculations are done for the second run and combined with results of the first run. The probable change (i.e., 97.7%) for the combination is then:

$$\Delta MTF = M - 2S$$

or

$$\Delta CEF = M - 2S$$

or

$$\Delta PDL = M - 2S$$

For RMS:

$$M_1 = [R + C_1(50.0)]^2 - R^2$$

$$S_1 = [R + C_1(84.1)]^2 - [R + C(50.1)]^2$$

where R is the nominal RMS (the same for both runs). After finding M and S, the probable change for the combination is

$$\Delta RMS = \sqrt{R^2 + M + 2S} - R$$

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Radial and Tangential MTF

Although the default orientation in TOR is tangential only, both radial and tangential are important in most systems. Thus, unless MTF is specified in one orientation only, it is recommended that both orientations be included in the TOR analysis. This is typically done by duplicating the fields in the lens specification and/or by adding a zoom position to get the necessary number of fields, and then specifying radial and tangential orientations as appropriate in the TOR run.

MTF for 45-degree Targets

Specifications are occasionally written to include, or exclusively use, 45° oriented targets. TOR allows this or any other angle to be used. It is noteworthy that 45° modulation is **not** necessarily comparable to the average of radial and tangential targets and may be higher or lower than both. Note that the angle is measured from the X axis. Thus, RADIAL corresponds to 0° and TANGENTIAL to 90°. The terms RADIAL and TANGENTIAL are defined for fields in the Y-direction only. If you have a field in the X direction for a rotationally symmetric lens and want radial MTF, you need to enter an azimuth of 90°.

Depth-of-Focus Tolerancing

In cases where the MTF requirement is specified over a focal range, a suggested approach is to set up a two position zoom where the back focus is zoomed to each end of its range. The back focus may also be used as a compensator in this case. It is strongly recommended that both radial and tangential MTF be used. The default assumption of tangential only will probably give optimistic results.

Isoplanatism and OSC

In all CODE V diffraction calculations (CEF, ALI, LSF, MTF, PAR, PMA, PSF, TOR, and WAV options), a test is made if Offense against the Sine Condition - OSC - is sufficient to potentially affect results. In particular, any program that deals with extended objects (MTF, PAR) depends upon isoplanatism (constancy of the point image patch as the field changes over the width of the object, e.g., over enough cycles of the MTF target to integrate properly); isoplanatism is destroyed by significant OSC residuals. In CODE V, special programming has been incorporated to represent the local intensity and magnification changes that occur with OSC, so that any wavefront and point image is correctly apodized and calculated for all of the listed options, even in the presence of large OSC; for example, an f/0.3 parabola would have massive OSC. This special process is valid in all forms of calculation (convolution, FFT, etc.) and has little effect on compute time.

TOR Considerations for Microlithographic Systems

When using TOR to analyze microlithographic systems, it's useful to keep the following information in mind:

- The Zernike metric in TOR does not normally include the tilt terms (the 2nd and 3rd Zernike terms), so that it will agree with RMS wavefront error calculations that always remove the tilt from the wavefront. For lithographic systems, it may be desirable to include the tilt terms in the RMS wavefront error calculation. This can be done by including the keyword, TIL, in the ZRN, ZFR, and ZFE commands.
- A singular value decomposition (SVD) algorithm determines the compensator solutions in the following features: Alignment Optimization (Analysis > Fabrication Support > Alignment Optimization menu, or ALI option) and Wavefront Differential Tolerancing (Analysis > Tolerancing menu, or TOR option). The default value for the singular value decomposition threshold (SVT) is 1.0e-10; this value is larger than the machine precision and is a good starting value. It will be necessary to try different values of SVT to optimize the compensation. As SVT becomes larger, the size of the compensators becomes smaller and the compensation becomes less complete. However, TOR is so fast that even if you have to explore different values of SVT before making a decision, it is still much faster than using finite differences. Changing the value of SVT does not delete the TOR coefficients, so repeating the ray tracing is not necessary.

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- Another important parameter is the maximum value for each of the compensators. Since the SVD algorithm (which uses SVT) is trying to restrict the compensator values, a recommended approach is to make the compensator limits loose and let the SVD algorithm limit the values. (Allowing the SVD algorithm to limit the motion of the compensators tends to yield more stable results than "trapping" the constraints between hard limits). If necessary, tight limits on a subset of the compensators can be used.
- The maximum number of compensators (MCP) is useful if the goal is to use a subset of compensators and it is not clear which ones to use. When MCP is less than the total number of compensators specified, the compensation algorithm will drop the least useful compensators to arrive at the number of compensators specified by MCP. The cost of this is that the performance will degrade. A typical approach to using MCP is to start with all the compensators and run TOR, incrementally reducing the MCP value until the performance is just at the required level. That value of MCP will be the minimum number of compensators needed.
- If distortion is an issue, a weight on the distortion (WTD) is suggested. The default value for this parameter is zero. When the value is greater than zero, the distortion is included in the compensation calculation. The effect is to reduce the distortion at the expense of the performance. It may be necessary to vary both WTD and SVT to find the optimum solution.

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