CODE V Introductory Seminar: Day 5

Tolerance Analysis Macros and Commands

OPTICAL RESEARCH ASSOCIATES
3280 East Foothill Boulevard
Pasadena, California 91107 USA
(626) 795-9101 Fax (626) 795-0184
e-mail: service@opticalres.com
World Wide Web: http://www.opticalres.com

Section 13
Tolerance Analysis

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Tolerancing Objective

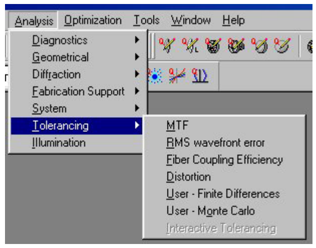
- Determine the allowed dimensional variations of lens parameters which
  - Minimizes manufacturing costs
  - Satisfies performance goals
- In other words
  - **How well do I need to build my lens?**

Some Reasons (Excuses?) for Avoiding Tolerancing

- Tolerancing is no fun for the designer
- Tolerancing is labor- and computer-intensive
- It's often easier to ask the shop what they can do, and put that on the prints
- The cost benefits are real but hard to assess
- Most tolerancing programs do not simulate the assembly and alignment process
  – This leads to tighter tolerances than would otherwise be required

CODE V's Tolerancing options overcome all these problems

CODE V’s Tolerancing Options



- **Analysis > Tolerancing** allows you to choose CODE V’s primary option for calculating the effects of manufacturing and assembly errors on either
  - **MTF**
  - **RMS wavefront error** *or*
  - **Fiber Coupling Efficiency**
- Command is **TOR**, which comes from Tolerancing, Ray-based (as opposed to paraxial-based tolerancing)

CODE V’s Tolerancing Options (cont.)

- CODE V has other tolerancing options (not covered in this seminar)
  - **Distortion**: tolerancing on chief ray distortion (**TOD**)
  - **User - Finite Differences**: macro for finite-difference tolerancing using user-defined performance measures (**TOLFDIF**)
  - **User - Monte Carlo TOLMONTE** : Macro for Monte Carlo-based tolerance analysis to simulate production yield using user-defined performance measures (**TOLMONTE**)
  - **TOL**: tolerancing on first-order properties and third-order aberrations (commands only)

Summary of TOR Advantages

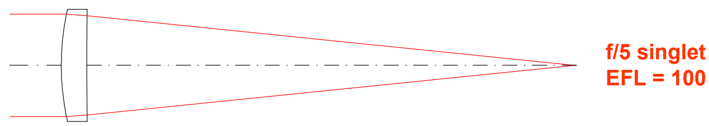
- Applicable to both diffraction-limited and non-diffraction-limited systems
- Direct calculation of manufacturing error-induced changes in polychromatic MTF or RMS wavefront error
  – Relates tolerances to final use performance specifications
- Uses compensating parameters to simulate the assembly and alignment process
  – Compensators can also be used to force boresighting
- Provides a default set of tolerances if none are already specified
- Two modes of operation:
  – **Sensitivity mode** - computes the effects of specified tolerances on performance
  – **Inverse mode** - computes the tolerance values so each tolerance has approximately the same impact on performance (default mode)

Summary of TOR Advantages (cont.)

- Provides statistical summary of system performance
  – Probability of achieving various MTF, RMS, or coupling efficiency levels
- Based on real ray trace using exact wavefront differentials
- Interactive tolerancing
  – Sensitivity coefficients are saved after initial run
  – Allows quick recalculation when tolerance value is changed
  – Spreadsheet style for rapid “what if” tolerancing

What Does TOR Actually Do?

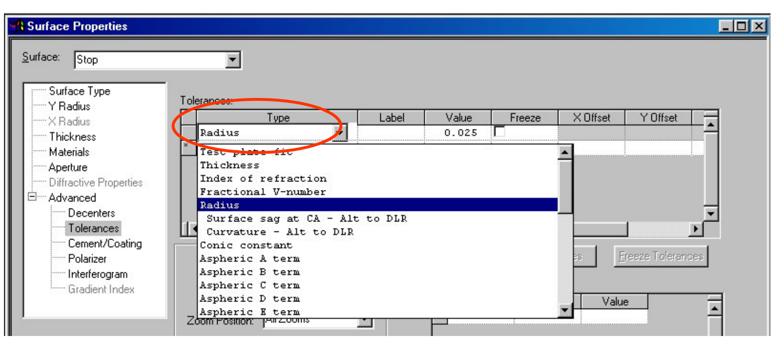
- Here is a simplified one-parameter example



- We will look at the change in MTF at 10 lp/mm for a change in front radius
  - Radius value is 50.0 mm
  - Nominal MTF at 10 lp/mm = 0.655
  - The default action will be to solve for the radius tolerance value which drops this MTF by 0.01 (to 0.645)

Singlet - No Compensators

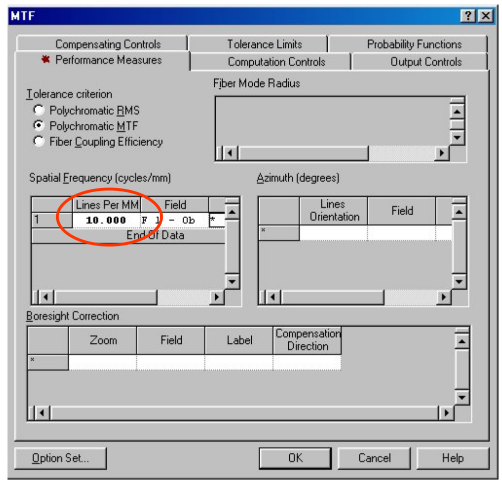
- First, specify a radius tolerance on surface 1
  - **Surface Properties > Tolerances** then select **Radius** from drop down menu
  - Command is `DLR S1` (Note that normally a value would be entered, but we will accept the default value since it will be changed anyway)



Singlet - Calculate Tolerances

- Calculate tolerances using **Analysis > Tolerancing > MTF** and enter the frequency as **10** lines per mm on the **Performance Measures** tab
- Commands are:

  TOR
  FRE 10
  GO



Singlet - Tolerance Results

- Output:

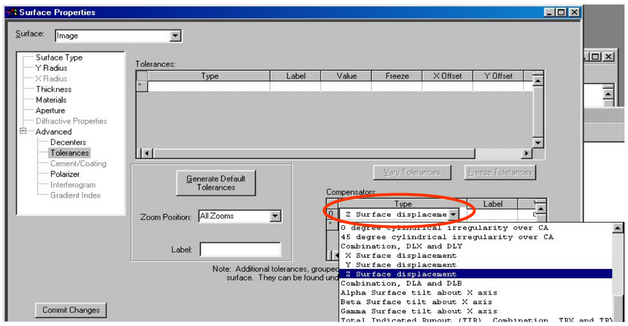
```
   MANUFACTURING ERROR            CHANGES IN MTF FOR
                                  PLUS AND MINUS
TYPE             CHANGE        MANUFACTURING ERRORS

DLR S1         0.0200000v         0.021     -0.026
```

- This change in radius (20 microns) is very tight (0.04%), and it still exceeds the allowed default 0.01 drop in MTF

Singlet - Focus Compensators

- Now add a focus compensator (defocus) by selecting **Tolerances** on the **Surface Properties** dialog box for the Image surface and selecting **Z surface displacement** as a compensator. Repeat the tolerance calculation.



- Commands: **CMP DLZ SI** ! DLZ is delta shift along Z
  TOR; FRE 10; GO

Compensated Singlet - Tolerance Results

- Output:

MANUFACTURING ERROR		CHANGES IN MTF FOR		COMPENSATING PARAMETERS
		PLUS AND MINUS		
TYPE	CHANGE	MANUFACTURING ERRORS		DLZ S3
DLR S1	0.2000000v	0.000	0.000	0.411637

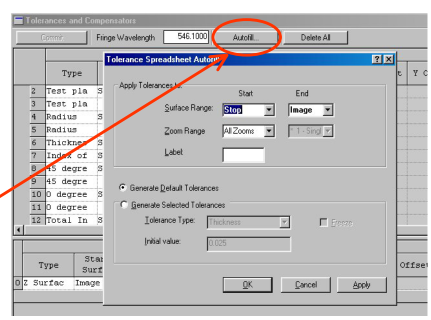
- This tolerance is 10X greater than before (0.20 mm), and has virtually no effect on MTF (the tolerance reached its maximum default limit)
- It does, however, require refocusing by 0.412 mm

What Does This Example Show Us?

- MTF tolerancing option is easy to use
- Compensation is crucial
  - Compensation allows looser tolerances, while maintaining performance
- A singlet with only one parameter is unrealistic
  - A singlet may have up to 18 default tolerances associated with it!
- Realistic tolerance limits are needed
  - CODE V has default limits which can be overridden
- Errors occur in random combinations, but the basic sensitivity data for any system is calculated as in this example
  - One parameter at a time
  - Compensation for each parameter
  - Statistics are applied after basic sensitivities are calculated

Default Tolerances

- If you don't specify any tolerances or compensators before executing an **Analysis > Tolerancing** option, CODE V first generates default tolerances and compensator
  - Automatically dissects the lens into elements and groups
  - Default tolerances are applied to each surface, element, and group
  - Focus shift is the default compensator
- Can also generate default tolerances for a surface or range of surfaces with **Review > Tolerances** and selecting **Autofill**



Workshop 16 - Tolerance the Tessar Lens

1. Restore the optimized Tessar.
2. To run a tolerance analysis on this lens, you must first determine what spatial frequency is appropriate. Run MTF on this lens and select an appropriate frequency (such as where the MTF is around 50%).
3. Make a tolerance analysis run using the default tolerances and the default compensator (defocus, which is the z displacement of the image surface). Is the performance after adding tolerances still reasonable?

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Sensitivity Coefficients

- TOR computes the MTF vs. a parameter change ΔP as
  $MTF(\Delta P) = A\ \Delta P^2 + B\ \Delta P + C$
- TOR computes RMS wavefront error vs. a parameter change ΔP as
  $RMS(\Delta P) = [\ A\ \Delta P^2 + B\ \Delta P + C\ ]^{1/2}$
- TOR computes coupling efficiency vs. a parameter change ΔP as
  $CEF(\Delta P) = A\ \Delta P^2 + B\ \Delta P + C$
- The A and B coefficients are the quadratic and linear sensitivity coefficients
  - These are computed for each tolerance for each field and zoom
  - The C term is the nominal value of MTF or RMS^2 (variance)

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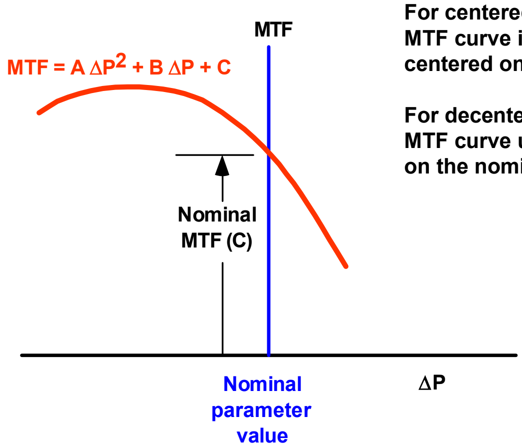
MTF vs. Tolerance



For centered tolerances, the MTF curve is not always centered on the nominal value

For decentered tolerances, the MTF curve usually is centered on the nominal value

Semi-Automatic Tolerancing

- By using **TOR**'s experience-based default assumptions, most of the tedious parts of tolerancing are automated
- Total default runs are useful for first tolerance runs as indicators of possible performance loss
  - User should then modify or add to the default tolerances or compensators for a more accurate analysis

Default Operation of TOR

- User selects quality criterion (MTF, RMS, Fiber coupling efficiency - one type per run)
  - Specify spatial frequency for MTF (most common case)
  - "No input" will imply use of RMS wavefront error (default)
  - Specify output fiber mode radius for coupling efficiency (input fiber mode simulated by pupil apodization)
- **TOR** then specifies tolerance bounds (minimum and maximum)
  - Default bounds are based on ORA's engineering experience

Default Operation of TOR (cont.)

- TOR then does an inverse sensitivity analysis
  - The goal is that each parameter contributes approximately equally to the loss in performance
  - The A and B sensitivity coefficients are computed for each tolerance, including the effects of the compensator
  - Using these, the value of each tolerance which results in the specified change in performance is determined (the default change is 0.01)
  - If the value is larger than the upper bound, it is set to the upper bound (the change in performance will be less than the specified change)
  - If the value is lower than the lower bound, it is set to the lower bound (the change in performance will be larger than the specified change)
  - The tolerances are rounded to 1 or 2 significant digits
- TOR then computes the statistics
  - Tolerances assumed to occur randomly within calculated ranges
  - Probability distributions depends on type of parameter (most are uniform)
  - Computes probabilities of achieving different levels of performance

Default Operation of TOR (cont.)

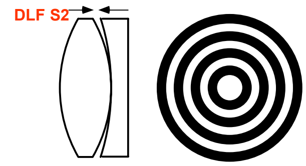
- TOR then creates output tables
  - Tables of sensitivities (with compensation)
    - Listed separately for each field and zoom
  - Tolerance tables
    - Centered tolerances
    - Decentered tolerances
  - Performance summary
    - Design vs. predicted as-built performance
- TOR lastly modifies the lens database
  - Modified tolerances and cross terms retained
  - These can be saved in .LEN file
  - The cross term matrix can be used later for interactive tolerancing

Tolerance Types

- Tolerances on **single surfaces**
  - Radius, thickness, index, etc.
- Tolerances on **elements**
  - Wedge
- Tolerances on **components** (single elements or cemented elements)
  - Decenter, tilt, etc.

Single Surface Tolerances

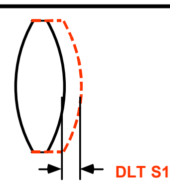
- Changes in radius
  - **DLR** (delta radius)
  - **DLC** (delta curvature)
  - **DLS** (delta sag at clear aperture)
  - **DLF** (delta fringe - test plate fit)
  - **IRR** (cylindrical irregularity in fringes)
    - **CYN** (cylinder normal - oriented at 0°)
    - **CYD** (cylinder diagonal - oriented at 45°)



- Changes in refractive index
  - **DLN** (delta index)
  - **DLV** (delta V value - only used if there are three wavelengths or more)
  - **HOM** (homogeneity)
  - **AXG** (axial index gradient)
  - **RAG** (radial quadratic index gradient)

Single Surface Tolerances (cont.)

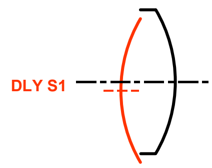
- **DLT** (change in thickness)



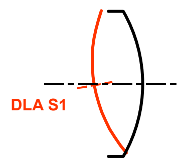
- Change in aspheric coefficients (can be applied to any surface type)
  - **DAK** (delta conic constant)
  - **DAA** (delta A - 4th order coefficient)
  - **DAB** (delta B - 6th order coefficient)
  - **DAC** (delta C - 8th order coefficient)
  - **DAD** (delta D - 10th order coefficient)
  - **DAE** (delta E - 12th order coefficient)
  - **DAF** (delta F - 14th order coefficient)
  - **DAG** (delta G - 16th order coefficient)
  - **DAH** (delta H - 18th order coefficient)
  - **DAJ** (delta J - 20th order coefficient)

Single Surface Decenter and Displacement Tolerances

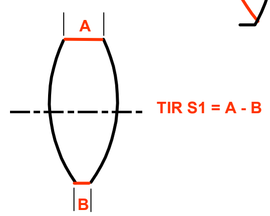
- Decentration tolerances
  - **DEC** (decenter)
    - **DLX** (delta shift in X)
    - **DLY** (delta shift in Y)
  - **DLZ** (delta shift in Z)



- Tilt tolerances
  - **TIL** (tilt)
    - **DLA** (delta tilt in alpha in radians)
    - **DLB** (delta tilt in beta in radians)
  - **DLG** (delta tilt in gamma in radians)

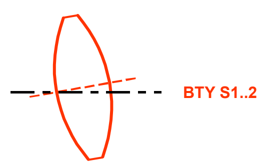


- Wedge tolerances
  - **TIR** (total indicated reading)
    - **TRX** (TIR in X)
    - **TRY** (TIR in Y)

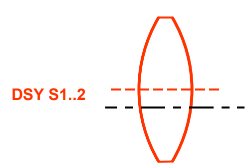


Group Decenter and Displacement Tolerances

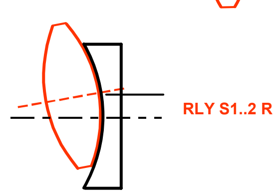
- Group tilt
  - **BTI** (barrel tilt in radians)
    - **BTX** (barrel tilt in X in radians)
    - **BTY** (barrel tilt in Y in radians)
  - **BRL** (barrel roll about Z in radians)



- Group displacement
  - **DIS** (displacement)
    - **DSX** (displacement in X)
    - **DSY** (displacement in Y)
  - **DSZ** (displacement in Z)

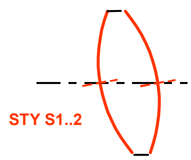


- Group roll (cemented surfaces)
  - **ROL** (roll)
    - **RLX** (roll in X)
    - **RLY** (roll in Y)



Group Tolerances (cont.)

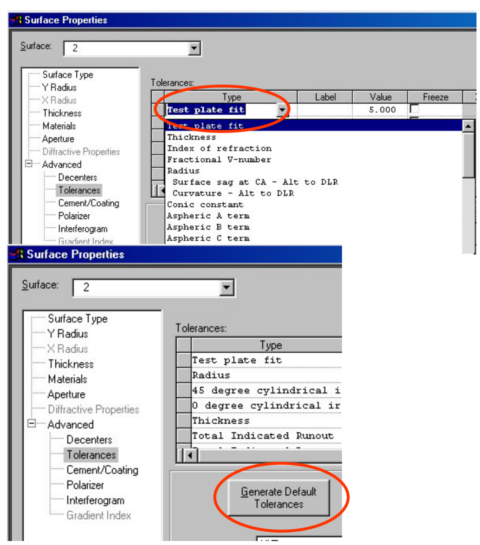
- **DOL** (delta overall length - change is divided among each surface)
- **STI** (shear tolerance - each surface is independently tilted)
  – **STX** (shear in X)
  – **STY** (shear in Y)



Entry of Tolerances - Surfaces

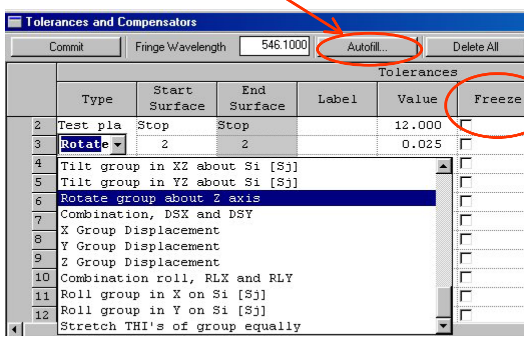
- In **Surface Properties** dialog box, select **Tolerances** and use drop down menu to add specific tolerances for that surface

- Use **Generate Default Tolerances** button to add all default tolerances for that surface



Entry of Tolerances - Groups

- Use Review > Tolerances
  - Enter specific tolerances using drop-down menu
  - Select Autofill to generate default tolerances, or selected tolerances for a surface range



Check box to freeze tolerance at current value in inverse sensitivity mode

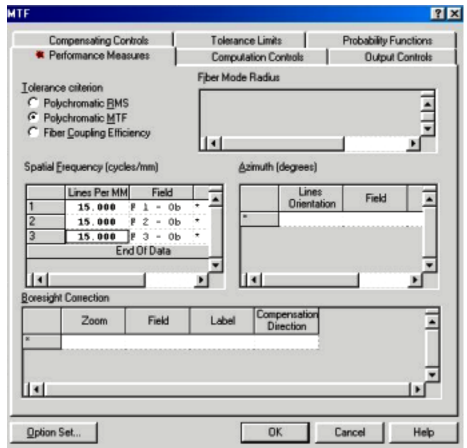
Compensators

- Compensators simulate adjustments made during assembly or alignment
- Compensators minimize the change (loss) in performance
  - They are not allowed to improve the performance by themselves but only to minimize performance loss
- Compensation is done simultaneously over field and zoom (by default)
  - Can specify compensation to be done separately for each field and zoom
- Any parameter that can be a tolerance can be a compensator
  - Most compensators relate to moving an element or group of elements (shift along Z, tilt, decenter, etc.)
  - Default compensator is shift of the image surface (DLZ SI)
- Tolerances and compensators can have labels
  - Compensators with labels only compensate for tolerances with the same label

TOR Sample Run

- Lens is f/4.5 Cooke Triplet
- Default **TOR** run on MTF at 15 lp/mm (**TOR** will generate the tolerances)
- Inverse sensitivity mode (default 0.01 drop in MTF per tolerance)
- Select **Analysis > Tolerancing > MTF** and enter frequency for each field
- Commands:

```
RES CV_LENS:COOKE1
TOR; FRE 15
FUL; GO
```



TOR Output Header (for each field)

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

      Cooke Triplet f/4.5

-------------------------------------------------------------------------------------
                                                   WAVELENGTH   WEIGHT   NO. OF RAYS
   FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG  656.3 NM    1        184
   FIELD WEIGHT =  1.00                              546.1 NM    2        192
                                                     486.1 NM    1        196

      FREQUENCY =   15.00 L/MM
      AZIMUTH   =  TANGENTIAL

      DIFFRACTION LIMITED MTF = 0.955
      NOMINAL MTF             = 0.925
                                                     MTF = A*T**2 + B*T + C

                                              (T=SCALE FACTOR FOR CHANGE)

                                                          C = 0.925330

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

field information

best possible MTF with current apertures

check for reasonable number of rays (too few may indicate aperture problems)

actual MTF for this field

TOR Output (per field)

tolerance types and values — *effects on MTF* — COMPENSATING PARAMETERS — *defocus compensation*

MANUFACTURING ERROR TYPE	CHANGE	CHANGES IN MTF FOR PLUS AND MINUS MANUFACTURING ERRORS		DLZ S7	A	B
DLF S1	12.0000000v	0.003	-0.009	-0.234222	-0.003028	0.006362
DLF S2	4.0000000v	-0.006	0.001	0.086491	-0.002276	-0.003563
DLF S3	4.0000000v	0.006	-0.007	-0.123458	-0.000622	0.006435
DLF S4	4.0000000v	-0.006	0.004	0.115538	-0.001121	-0.005250
DLF S5	10.0000000v	0.004	-0.010	-0.170460	-0.003063	0.006609
DLF S6	8.0000000v	-0.007	0.004	0.122101	-0.001105	-0.005459
DLR S1	0.0600000v	-0.009	0.003	0.227718	-0.002862	-0.006186
DLR S2	1.0000000v	0.001	-0.009	-0.119314	-0.004331	0.004915
...						
DSY S3..4	0.0200000v	-0.021	-0.021	0.000000	-0.021328	0.000000
DSX S3..4	0.0200000v	-0.007	-0.007	0.000000	-0.007493	0.000000
TRY S5	0.0300000v	-0.008	-0.008	0.000000	-0.007508	0.000000
TRX S5	0.0300000v	-0.003	-0.003	0.000000	-0.002527	0.000000
BTY S5..6	0.0003000v	0.000	0.000	0.000000	-0.000148	0.000000
BTX S5..6	0.0003000v	0.000	0.000	0.000000	-0.000053	0.000000
DSY S5..6	0.0200000v	-0.012	-0.012	0.000000	-0.011907	0.000000
DSX S5..6	0.0200000v	-0.004	-0.004	0.000000	-0.004252	0.000000

PROBABLE CHANGE IN MTF -0.089

PROBABLE CHANGE OF COMPENSATORS (+/-) 0.797387

sensitivity coefficients

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Probability Summary (for each field)

```
PROBABLE CHANGE IN MTF        -0.089

         PROBABLE CHANGE OF COMPENSATORS (+/-)                   0.797387

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

  The probable change in MTF assumes a uniform distribution of manufacturing
  errors over the range for all parameters except tilt and decenter
  which have a truncated Gaussian distribution in X and Y

       CUMULATIVE         CHANGE
      PROBABILITY         IN MTF
       50.0 PCT.          -0.033       * If it is assumed that the errors can
       84.1 PCT.          -0.061         only take on the extreme values
       97.7 PCT.          -0.089 *       of the tolerances, the 97.7 percent
       99.9 PCT.          -0.117         probable change in MTF is -0.226
```

probability of achieving different levels of performance

sort of like a worst case

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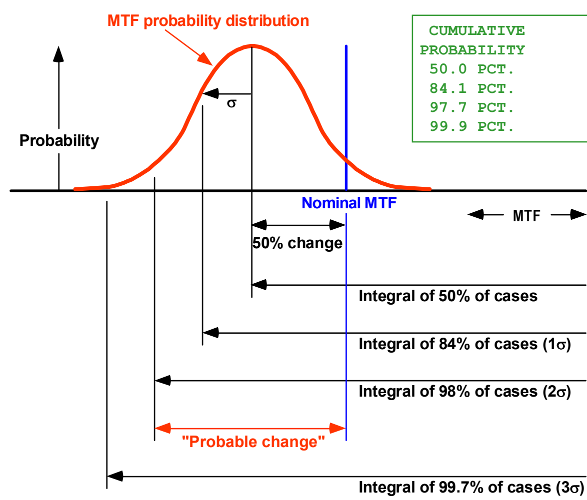
Performance Prediction

- For each field, a probability summary is generated of the probabilities of achieving given levels of performance
  - Includes cross terms (effects of one tolerance on another)
- These are dependent on the probability distributions of the individual tolerances
  - Most tolerances use a uniform distribution
  - Tilts and decenters use a truncated Gaussian distribution
  - These can be changed by class (symmetric, irregularity, or decentered)
    - Can be changed to uniform, Gaussian, end point only, or to specific 2nd and 4th order moments
- The performance distribution calculation is based on statistical summing which results in a Gaussian performance distribution
  - 2σ point (97.7%) is labeled “Probable change”
  - It means that 97.7% of the fabricated systems will have this performance loss <u>or less</u>

Performance Prediction (cont.)



CUMULATIVE PROBABILITY	CHANGE IN MTF
50.0 PCT.	-0.033
84.1 PCT.	-0.061
97.7 PCT.	-0.089
99.9 PCT.	-0.117

Centered Tolerances Table

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

Cooke Triplet f/4.5

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)
1	21.48138	0.0600	12.0/ 3.00	2.00000	0.20000	SK16	0.00100	0.80
2	-124.10000	1.0000	4.0/ 2.00	5.26000	0.02000			
3	-19.10000	0.0400	4.0/ 1.50	1.25000	0.02000	F4	0.00100	0.80
4	22.00000	0.0600	4.0/ 2.00	4.69000	0.02000			
5	328.90000	14.0000	10.0/ 3.00	2.25000	0.04000	SK16	0.00200	0.80
6	-16.70000	0.0200	8.0/ 3.00	43.05048				
7				0.02893				

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

these default limits can be changed by the user

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Decentered Tolerances Table

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

Cooke Triplet f/4.5

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	21.48138	-124.10000	0.0020	0.5	0.0041	1.0	0.0152	0.0200
2	-19.10000	22.00000	0.0020	0.8	0.0027	1.0	0.0178	0.0200
3	328.90000	-16.70000	0.0300	7.9	0.0039	1.0	0.0169	0.0200

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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Performance Summary

P E R F O R M A N C E   S U M M A R Y

POLYCHROMATIC MODULATION TRANSFER FUNCTION

Cooke Triplet f/4.5

performance loss expected with these tolerances and compensators

WAVELENGTH	WEIGHT
656.3 NM	1
546.1 NM	2
486.1 NM	1

RELATIVE FIELD	FREQ L/MM	AZIM DEG	WEIGHT	DESIGN	DESIGN + TOL *	COMPENSATOR RANGE (+/-) * DLZ S7
0.00, 0.00	15.00	TAN	1.00	0.927	0.838	0.797387
0.00, 0.69	15.00	TAN	1.00	0.459	0.409	0.797387
0.00, 1.00	15.00	TAN	1.00	0.371	0.312	0.797387

note common compensator value used across fields

* 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.

How TOR Uses Sensitivity Coefficients

- The A and B sensitivity coefficients allow TOR to quickly recompute the change in performance for different values of a tolerance
- Each tolerance has a value and associated A and B sensitivity coefficients
- The change in MTF (for example) is computed as

  $\Delta MTF = AT^2 + BT$
  where T is a scale factor for the tolerance value (nominal value is T = 1)
- For example:

MANUFACTURING ERROR		CHANGES IN MTF FOR PLUS AND MINUS				
TYPE	CHANGE	MANUFACTURING ERRORS		DLZ SI	A	B
DLF S1	12.0000000v	0.003	-0.009	-0.234222	-0.003028	0.006362

- What is ΔMTF for DLF 24? Note that T= ±2

  for +24 fringes: $\Delta MTF = (-0.0032028)*2^2+(0.006362)*2 = -0.0000872$
  for -24 fringes: $\Delta MTF = (-0.0032028)*(-2)^2+(0.006362)*(-2) = -0.0255352$
  The compensator value is linear (scales as ±T)

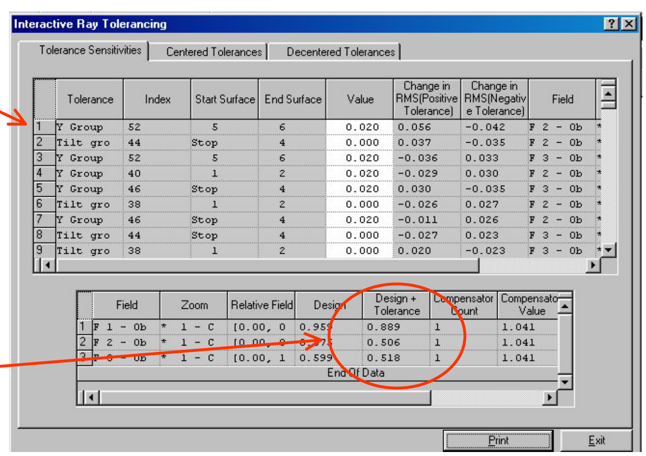
Interactive Tolerancing

- The use of sensitivity coefficients to recompute the effects on performance allows rapid recomputation after changing tolerance values
  - Allows “what-if” tolerancing
  - You can tighten some tolerances and loosen others and immediately see the impact on performance
- A special spreadsheet view allows easy changing of tolerance values and display of resulting performance
  - This is referred to as Interactive Tolerancing
  - The tolerances in the spreadsheet are sorted according to impact on performance (worst to best)
  - As any tolerance is changed, the performance is recomputed, and the tolerances are resorted
- Select **Analysis > Tolerancing > Interactive Tolerancing**

Interactive Tolerancing Spreadsheet

Tolerances listed by impact on MTF

Performance summary updated when tolerances are changed



RMS Wavefront Error

- W = Nominal wavefront
- W' = Perturbed wavefront
- Change in RMS = RMS (W') - RMS (W)
- RMS of change in wavefront = RMS (W' - W)
- These two are equal only if W = 0

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RMS Wavefront Error Example

- Nominal system has 2 λ RMS of spherical aberration
- Tolerance introduces 1 λ RMS of spherical aberration and 1 λ RMS of coma

RMS (W) = 2

RMS (W'-W) = $[(1)^2 + (1)^2]^{1/2}$ = 1.4

RMS (W') for plus tolerance = $[(2+1)^2 + (+1)^2]^{1/2}$ = 3.2
3.2 - 2 = 1.2

RMS (W') for minus tolerance = $[(2-1)^2 + (-1)^2]^{1/2}$ = 1.4
1.4 - 2 = -0.6

CHANGES IN RMS FOR PLUS AND MINUS MANUFACTURING ERRORS		RMS OF CHANGE IN WAVEFRONT
1.2	-0.6	1.4

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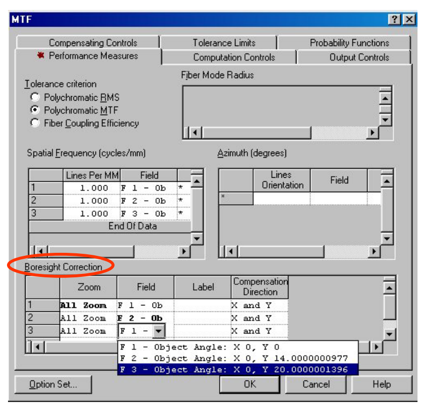
RMS Wavefront Error Output

COMPENSATING PARAMETERS

MANUFACTURING ERROR TYPE	CHANGE	CHANGES IN RMS FOR PLUS AND MINUS MANUFACTURING ERRORS		RMS OF CHANGE IN WAVEFRONT	DLZ S7
DLF S1	2.0000000v	-0.007	0.007	0.009	-0.038792
DLF S2	2.0000000v	0.015	-0.013	0.021	0.041935
DLF S3	2.0000000v	-0.010	0.010	0.011	-0.061766
DLF S4	2.0000000v	0.015	-0.013	0.019	0.057719
DLF S5	2.0000000v	-0.007	0.008	0.010	-0.033538
DLF S6	2.0000000v	0.001	-0.001	0.004	0.030863
DLR S1	0.0200000v	0.014	-0.012	0.018	0.075429
DLR S2	0.2000000v	-0.008	0.008	0.011	-0.023140
DLR S3	0.0200000v	0.010	-0.010	0.012	0.062480

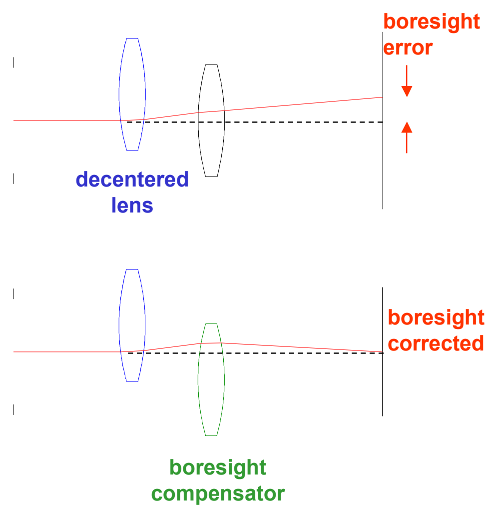
Boresight Correction

- In some systems, boresight (shift of image) is important
  – Usually caused by decentered tolerances (tilt, decenter, wedge, etc.)
- This can be controlled in **TOR** by specifying boresight correction (command: **BOR**)
  – Specified with **Analysis > Tolerancing > MTF** (or RMS) and selecting the **Performance Measures** tab and specifying which fields will have boresight correction



Boresight Example

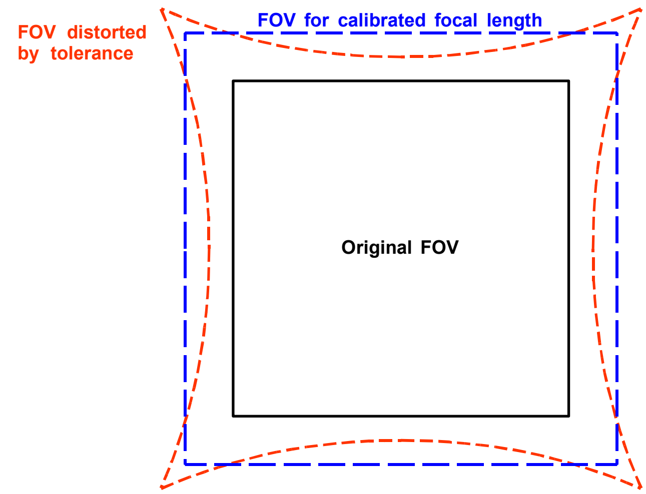
- Uses compensators (usually tilt or decenter of an element) to correct for boresight error
  - The boresight correction may cause additional performance loss
  - Additional compensators may be specified to minimize performance loss after boresight correction
- If boresighting is specified for an off-axis field (using centered compensators) then changes in focal length or magnification can be corrected



Distortion Calculation

- Tolerances may introduce distortion in addition to other performance loss
- The distortion can be separated into boresight and residual distortion
  - Boresight is normally introduced by decentered tolerances
  - All tolerances can introduce residual distortion
- The distortion component can be calibrated out as a change in focal length (or magnification) with smaller residual distortions
  - Calibration process may result in a different net boresight

Distortion (Centered Tolerances)



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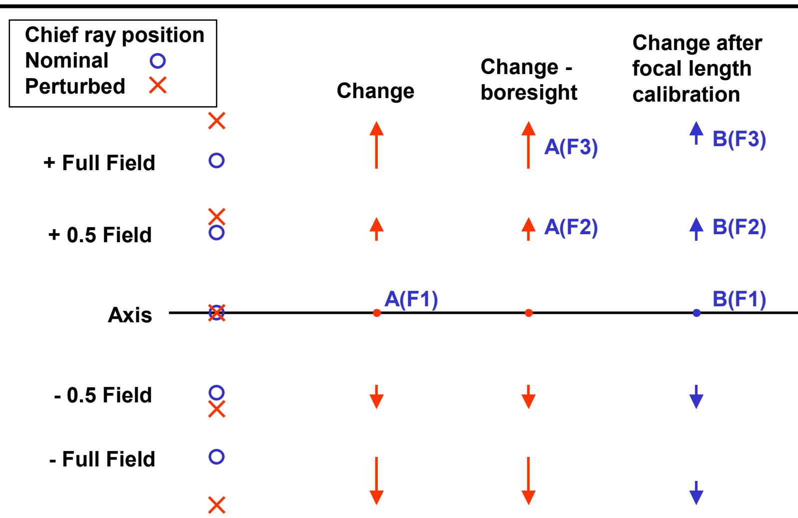
Distortion (Centered Tolerances) (cont.)



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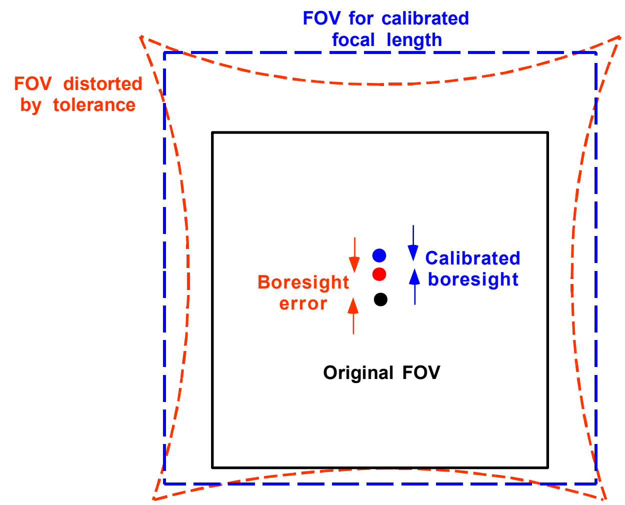
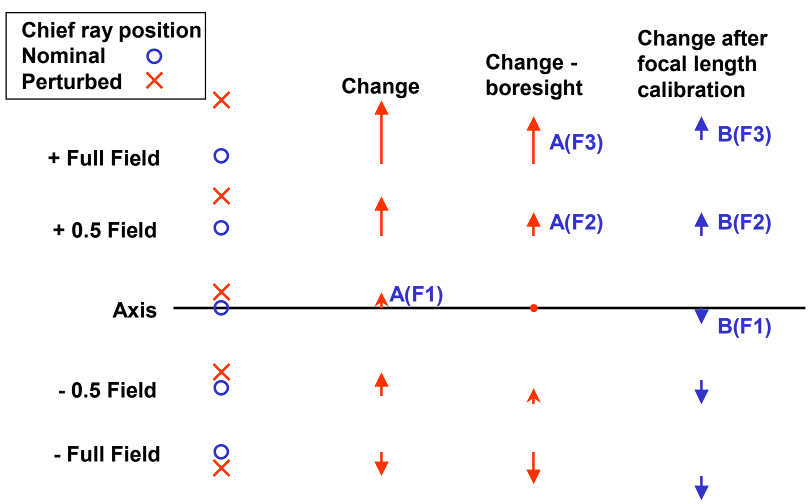
Distortion (Decentered Tolerances)



Distortion (Decentered Tolerances) (cont.)



Distortion Output

- Obtained by selecting **Distortion Evaluation** on **Output Controls** tab (Command: DST ALL in TOR)

```
                                                                     A - Uncalibrated distortion
                                                                     B - Calibrated distortion

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

DLF S1        12.000000                    A          0.000000     0.000000  0.000000
                                           B          0.000000     0.000000  0.000000

DLF S2         4.000000                    A          0.000000     0.000000  0.000000
                                           B          0.000000     0.000000  0.000000
... lines omitted

DSY S5..6      0.020000                    A          0.000000     0.000000  0.000000
                                           B          0.000000     0.000000  0.000000

DSX S5..6      0.020000                    A          0.033725     0.001230  0.002602
                                           B         -0.001301    -0.000071  0.001301

PROBABLE CHANGE                            A          0.106651     0.006793  0.014331
                                           B          0.006811     0.000652  0.006812
RSS calibration values:
    Scale change (fraction)         0.012451
    Rotation (radians)              0.000167
    X-shift (lens units)            0.096673
    Y-shift (lens units)            0.102028
```

off-axis residual distortions

off-axis residual distortions after calibration

boresight error after calibration

boresight error

RSS changes

Miscellaneous TOR Notes

- TOR is sensitive to focus
  - Lens should be at best focus before running TOR
    - Select **Analysis > Diffraction > Wavefront Analysis** and **Select Focus Mode** as **Best Focus**
    - Commands: WAV; RFO; GO
- For rotationally symmetric systems, **TOR** simulates opposite sides of the field
  - For non-rotationally symmetric systems, you should use plus and minus field points to define the FOV
- Usually, both radial and tangential MTF should be analyzed
  - If both are not calculated, compensation may improve MTF in one direction at the expense of MTF in the other direction
  - One way to compute both:
    - Enter off-axis fields twice
      YAN 0 10 10 20 20
    - In **TOR**, enter different MTF azimuths for duplicated fields
      AZI RAD RAD TAN RAD TAN

Workshop 17 - Tolerancing the Tessar Lens (again)

1. Restore the toleranced Tessar.
2. Assume the specification for MTF at 50 cycles/mm is as follows:

Field	MTF
0º	65%
14º	60%
20º	40%

   Use interactive tolerancing to try to achieve these goals.

3. Can any combination of tolerances reach these goals? If so, are the tolerances reasonable, or will they increase the cost of the lens?