

# Tolerance in CODE V

Opti 521 Presentation

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#### Outlines

- Abstract
- Summary of Tolerance in CODE V
- Typical procedure
- Tolerance Analysis in CODE V
- Demo
- Conclusion



#### Abstract

- Tolerance analysis is required to ensure system performance
- Each component in the optical system needs to be constrained with certain tolerance value
- CODE V provides complete tolerance analysis in three methods :
  - Wavefront Differential
  - Finite Difference
  - Monte Carlo Simulation



# **Tolerancing Methods**

#### Finite Difference:

changes each parameter within its tolerance range and predicts the system performance degradation on a tolerance-by-tolerance basis.

- Disadvantage:
  - Prediction of overall performance is likely too optimistic.
  - does not consider parameter changes simultaneously in multiple components



# **Tolerancing Methods**

• Monte Carlo:

change all of the parameters that have an associated tolerance by random amounts, but within each tolerance range.

- Advantage:
  - It considered at the same time, the Monte Carlo method accurately accounts for cross-terms
- Disadvantage:
  - The individual tolerance for each components can't be obtained using this method.



# **Tolerancing Methods**

- Wavefront Differential: (most common)
- Advantage:
  - It is very fast
  - provides information about both individual tolerance sensitivities (like the Finite Differences method)
  - an accurate performance prediction, including the effect of corss-terms(like the Monte Carlo method)



## Comparison

#### Table 1. CODE V's tolerancing methods

Algorithm	CODE V Feature	Supported Performance Metric	Supported Tolerances	Comments
Wavefront Differentials	TOR	<ul> <li>RMS Wavefront Error</li> <li>Diffraction MTF</li> <li>Fiber Coupling Efficiency into a SMF</li> <li>Polarization Dependent Loss into a SMF</li> </ul>	CODE V pre-programmed tolerances (e.g., DLR, DLT, TIR, BTI, etc.)	<ul> <li>Very fast</li> <li>Very accurate for tolerances that result in a small degradation in system performance (includes cross-terms)</li> <li>Provides individual tolerance sensitivities AND accurate performance prediction</li> <li>Both Inverse Sensitivity &amp; Sensitivity analysis supported</li> </ul>
Finite Differences	TOLFDIF	Any quantity that CODE V can compute	CODE V pre-programmed tolerances & User-defined tolerances	<ul> <li>Can be slow depending on number of tolerances, fields, zooms and type of performance metric analyzed.</li> <li>Provides accurate individual tolerance sensitivities, particularly for larger tolerances</li> <li>Performance summary is optimistic since this method does not include cross-terms.</li> <li>Performance summary is approximate since this method assumes that the performance variation is quadratic with tolerance. This assumption may not be valid for the requested performance metric</li> </ul>
Monte Carlo Simulation	TOLMONTE	Any quantity that CODE V can compute	CODE V pre-programmed tolerances & User-defined tolerances	<ul> <li>Can be slow depending on the number of trials requested and type of performance metric analyzed.</li> <li>Provides accurate performance prediction (if many trials are requested), but no information about individual tolerance sensitivities</li> </ul>



# **TOR Function**

- Sensitivity Mode
  - includes the effect of adjustable parameters specified by the user to simulate the assembly procedure
- Inverse Sensitivity Mode
  - the program can select an appropriate set of tolerance parameters, ranges for the parameters, and specific values that provides a predetermined individual MTF drop.
- RMS wavefront eroor & MTF



#### Procedure

- 1. Define quantitative figures of merit for requirements
- 2. Estimate component tolerances
- 3. Define assembly/alignment procedure and estimate tolerances
- 4. Calculate sensitivities
- 5. Estimate Performance
- 6. Adjust tolerances, balance cost and schedule with performance
- 7. Iterate with system engineer, fabricators, management



# Tolerance Analysis in CODE V

- 1. Start with the unperturbed system
- 2. Adjust the parameter whose tolerance is being evaluated at the minimum value
- 3. Adjust the compensator
- 4. Record the resulting criteria
- 5. Repeat the previous steps for maximum tolerance
- 6. Repeat the entire procedure again



## Example Demo

- An optical system that is used to focus a collimated HeNe laser beam onto a Position Sensing Detector (PSD)
- System Specification

Entrance Pupil Diameter = 20 mm Nominal EFL = 100 mm Wavelength = 632.8 nm(HeNe) Diffraction Limited Operation SR > 80% Adjustment Resolution is about (+/-) 5 µm



# Step 1: Opening the File

💷 Lens Data N	🗉 Lens Data Manager							
Surface #	Surface Name	Surface Type	Y Radius	Thicknes	55 Glass	Refract Mode	Y Semi-Aperture	
Object		Sphere	Infinity	Infinit		Refract	0	
Stop		Sphere	Infinity	0.0000		Refract	10.0000 <sup>O</sup>	
2		Sphere	58.6000	5.0000	SK15_SCH	Refract	12.5000 <sup>O</sup>	
3		Sphere	-277.0000	1.0000		Refract	12.5000 <sup>O</sup>	
4		Sphere	-97.0000	4.0000	SK15_SCH	Refract	12.0000 0	
5		Sphere	-174.0000	93.8292		Refract	12.5000 <sup>O</sup>	
Image		Sphere	Infinity	0.0000		Refract	0.0002 0	
		<u> </u>	End C	)f Data				
				γ				
🔛 Quick 2D La	beled Plot				🗒 List All Lens Da	ata		
🗘 酔 🐰	🖻 💼  🖬 🕚		Q & / A		0			
		-	1 -					
					INFINITE CON	JUGATES	<u> </u>	
					EFL	100.0135		
					BFL	93.8270		
					FFL	-99.5796		
	<b>—</b>				TMG DTS	93 8292		
					OAL	10.0000		
					PARAXIAL	IMAGE		
	+#+				HT	0.0000		
					ANG	0.0000		
					ENTRANCE	PUPIL		
					THT	20.0000		
					EXIT PUPI	L		
New Jane 6			13.00 38		DIA	20.0871		
New lens fro	New lens from CVMBARD:cvnewlens.seq Scale: 1.80 GRA 28-How-09 THI -6.6222							



#### Step 2: Analysis →Tolernacing→RMS Wavefront Error menu

🙀 CODE V - CodeV_doublet.len			Tolerancing - RMS	? ×
File Edit Lens Display Review Analy	vsis Optimization Tools V	Vindow Help		
🛛 🗅 🐸 🕑 🔏 🎒 🗛 🐇 🖻	Diagnostics •	🖾 🕼 🛛 😰 🤣 📢	Compensating Controls	Tolerance Limits Probability Functions
t 1 New lang from CVM44C	Geometrical +		Performance Measures	Computation Controls Output Controls
"I - New lens from CVMAC	Diffraction +	<u> </u>		Fiber Mode Radius
	Fabrication Support		Oleranse criterion     Poluchromatic BMS	
Command Window	System +		C Polychromatic MTF	
Review Spreadsheets	Tolerancing +	MTF	C Fiber Coupling Efficiency	
E- Listings	Illumination	RMS wavefront error	C Polarization Dependent Loss	
Analysis Windows		Fiber Coupling Efficiency	Spatial Frequency (cycles/mm)	Azimuth (degrees)
Tolerancing - RMS	Tolerance Analy:	Polarization Dependent Loss		
Quick 2D Labeled Plo	ORA 30-	Distortion		
- Plot Windows	100. J	User Einite Differencer		
Error Log		User - Pinite Differences		
	90	User - Monte Carlo		• • • •
	80	Interactive Folerancing		
			Boresight Correction	
			Zoom Field	Label Compensatio
			x	
				<b>&gt;</b>
			Option Set	OK Cancel Help



### Step 3: Compensation Control tab

Tolerancing - RMS		? X
Performance Measur	res Computation Controls Output Co	ontrols
🗮 Compensating Contro	ols Tolerance Limits Probability Fun	ictions
Field weight for field		
	Field Zeen	
× Weight		
	.do	
1		- -
Weight on linear term	Weight on distortion	sation
1.0000	× 0.0000	
	Y 0.0000	
Option Set	OK Cancel	Help

- Check the box where it says "Force Y symmetry for compensation".
- Ensure that the perturbation effect is considered the entire field of view instead of half field.



#### Step 4 : Computation Control tab



- single-click on the column where it says one under the "Inverse Sensitivity" mode.
- This will set the default decrease in performance to be 0.01 waves. This value can be modified to meet your specification.



## Step 5 : Output Controls tab

Tolerancing - RMS	? <mark>×</mark>
Compensating Controls Performance Measures	Tolerance Limits     Probability Functions       Computation Controls     * Output Controls
© Extended © Standard	Cut-off Performance Threshold          0.0100       Output Threshold         Decibel Scale       Distortion units
Draw Gridlines Line Style SPL Number of Trials	Distortion Evaluation Distortion evaluation None Label
500 Horizontal Axis Minimum O Horizontal Axis Maximum	Output to Buffer Buffer number
0.1 Horizontal Axis Increment 0.01	Distortion 2 Performance 3 Monte-Carlo 4
Option Set	OK Cancel Help

- choose the "*Extended*" output mode
- modify the

"Horizontal Axis Minimum", "Horizontal Axis Maximum", "Horizontal Axis Increment" option to adjust your plot scale



### Step 6 : Generate Plot





# Step 7 : Interpret the data

#### Possible Perturbation in DODE V

BTX	Tilt in X (in radians) of the group of surfaces about the pole of the first surface
BTY	Tilt in Y (in radians) of the group of surfaces about the pole of the first surface
	Cylinder (at 45 degrees) irregularity in fringes at 546.1 nm. over the clear
CYD	aperture
CYN	Cylinder (at 0 degrees) irregularity in fringes at 546.1 nm. over the clear aperture
DLF	Test plate fit (power) in fringes at 546.1 nm. over the clear aperture
DLN	Change of index of refraction
DLR	Change of radius in mm.
DLT	Change of thickness in mm.
DLZ	Axial displacement of the surface in mm.
DSX	Lateral displacement of the group of surfaces in the X-direction in mm.
DSY	Lateral displacement of the group of surfaces in the Y-direction in mm.
TRX	Total indicator runout in X (resulting in a surface tilt) at the clear aperture in mm.
TRY	Total indicator runout in Y (resulting in a surface tilt) at the clear aperture in mm.



#### Text File – Extended Mode

					RMS =	= SQRT (A*T**2	+ B*T + C)
					(T=SCA	ALE FACTOR FO	R CHANGE)
						C = 0	.000556
				CO	MPENSATING PARAMETER	s.	
					DLZ S6		
MANUFACTURING	ERROR	CHANGES I	N RMS FOR	RMS OF			
TYPE	CHANGE	MANUFACTUR	ING ERRORS	WAVEFRONT		A	В
DLF S2	2.0000000	0.0000	0.0000	0.0003	-0.043819	0.000000	0.000000
DLF S3	2.0000000	0.0000	0.0000	0.0004	0.041228	0.00000	0.000000
DLF S4	2.0000000	0.0000	0.0000	0.0009	-0.044359	0.00001	0.000000
DLF S5	2.0000000	0.0000	0.0000	0.0005	0.039019	0.000000	0.000000



#### **Centered Tolerance**

	30-Nov-09			C E N T E R T O L E R A N	ED			1	POSITION 1
	New lens	from CVMACR(	cvnewlens.seq	I					
		RADIUS	FRINGES		THICKNESS		INDEX	V-NO	INHOMO-
SUR	RADIUS	TOL	POW/IRR	THICKNESS	TOL	GLASS	TOL	(웅)	GENEITY
1				0.00000	0.50000				
2	58.60000	2.2000	2.0/ 0.50	5.00000	0.50000	SK15	0.00200		
3	-277.00000	34.0000	2.0/ 0.50	1.00000	0.50000				
4	-97.00000	1.9000	2.0/ 0.50	4.00000	0.50000	SK15	0.00200		
5	-174.00000	9.9000	2.0/ 0.50	93.82924					
6				0.00000					
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									



#### **De-centered Tolerance**

			DEC TOL	ENTERH ERANCH	E D E S			
	New lens from	CVMACRO:cvnewle	ns.seq					
ELEMENT	FRONT	BACK	ELEME	NT WEDGE	ELEME	NT TILT	EL.	DEC/ROLL(R)
NO.	RADIUS	RADIUS	TIR	ARC MIN	TIR	ARC MIN	TIR	mm.
1	58.60000	-277.00000	0.0700	9.6	0.0625	8.6	0.0517	0.1000
2	-97.00000	-174.00000	0.0200	2.9	0.0480	6.9	0.0104	0.1000
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.								



## Result

🕎 Tolera	ancing - RMS				
¢	X 🖻 💼				
CYN	S5	0.5000000v	0.0048	0.0048	0.0159
TRY	S2	0.0700000v	0.0093	0.0093	0.0229
TRX	S2	0.0700000v	0.0093	0.0093	0.0229
BTY	S23	0.0025000v	0.0048	0.0048	0.0157
BTX	S23	0.0025000v	0.0048	0.0048	0.0157
DSY	S23	0.1000000v	0.0069	0.0069	0.0193
DSX	S23	0.1000000v	0.0069	0.0069	0.0193
TRY	S4	0.0200000v	0.0097	0.0097	0.0235
TRX	S4	0.0200000v	0.0097	0.0097	0.0235
BTY	S45	0.0020000v	0.0095	0.0095	0.0232
BTX	S45	0.0020000v	0.0095	0.0095	0.0232
DSY	S45	0.1000000v	0.0069	0.0069	0.0193
DSX	S45	0.1000000	0.0069	0.0069	0.0193
RSS					0.0996

- Lens 1(DSX S2..3)
   DeCenter 1 = 0.0193 / 0.1 = 0.193 λ/mm
- Lens 2(DSX S4..5)
   DeCenter 2 = 0.0193 / 0.1 = 0.193 λ/mm
- Tilt1 = 0.0157/0.0025 rad = 0.0157 λ/0.143 degrees = 0.1096 λ/degree
- Tilt2 = 0.0232/0.002 rad = 0.0157 λ/0.143 degrees = 0.2025 λ/degree



## Comparison

33		
Parameters	CodeV TOR	Manual
Decenter1 (λ/mm)	0.193	0.19096
Tilt 1 (λ/degree)	0.1096	0.11325
Decenter2(λ/mm)	0.193	0.18794
Tilt 2 (λ/degree)	0.2025	0.19799



## Conclusion

- Shows that the sensitivity analysis obtained through the automatic "tolerance" button is actually really close to the values we got through manual perturbations.
- To minimize production cost, the ideal optical system design will maintain the required performance with achievable component and assembly tolerances, using well-chosen post-assembly adjustment.
- The unique suite of tolerancing capabilities in CodeV will do just the trick when building the ideal system.