
Optical software tutorials— OSLO

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Outline

- Introduction to OSLO
- Basic fundamental of OSLO
 - Example 1 : Cooke triplet
- Advanced fundamental of OSLO
 - Example 2 : four-prism configuration beam displacer (achromatic polarization preserving)
 - Example 3 : effective lens model of VCSEL (vertical cavity surface emitting lasers with whispering gallery mode)

Introduction to OSLO

-
- What is OSLO?
 - The advantages of OSLO
 - The computer interface of OSLO
 - What could be designed with OSLO?

What is OSLO?

- OSLO is an optical system design software. It can design geometrical (lens) optical systems and analyze the system and evaluate the performance, such as image quality.
- The method of ray tracing used in OSLO is sequential ray tracing, but it also can execute non-sequential ray tracing.
- It can execute the optimization and tolerance analysis.

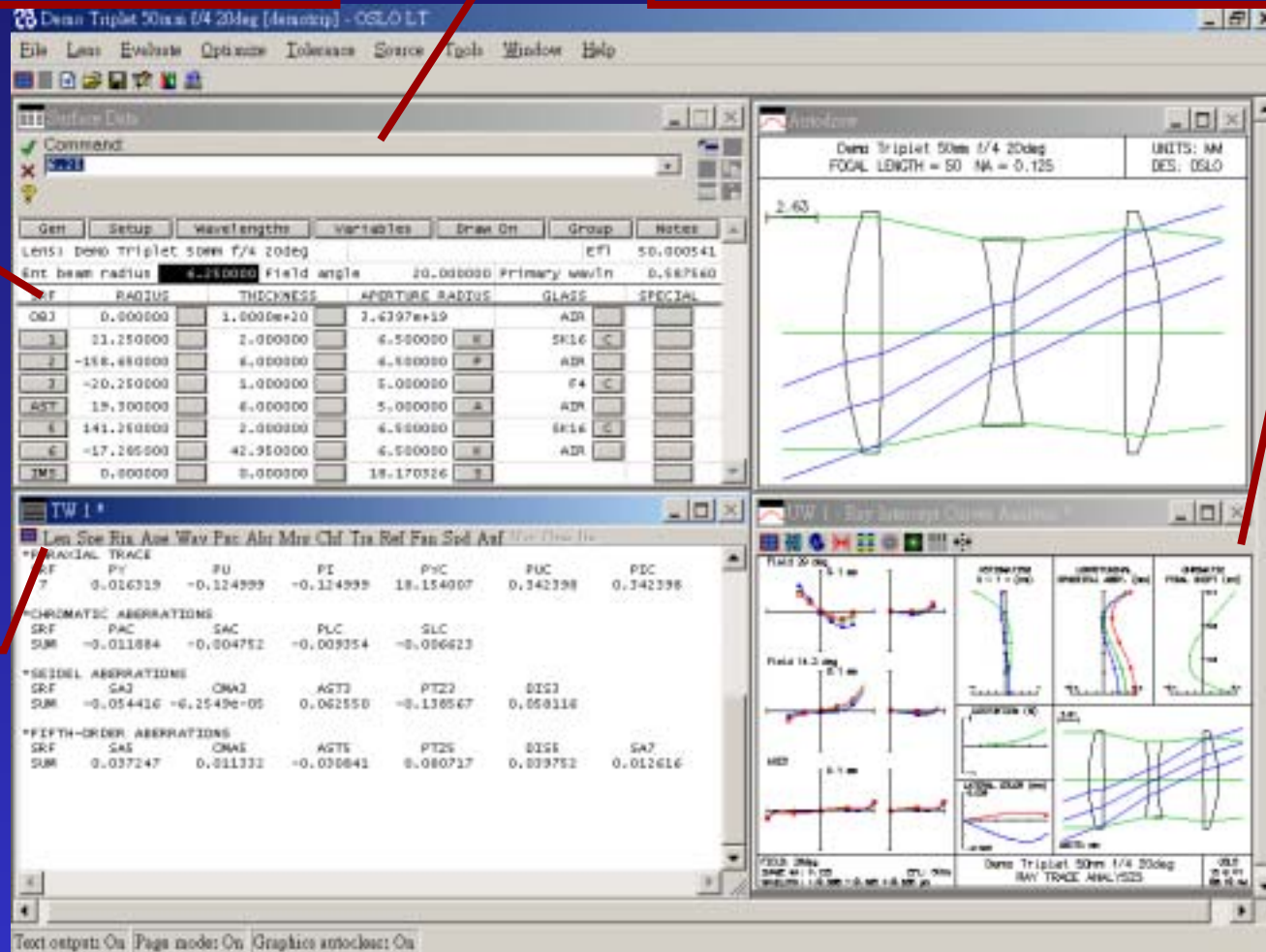
The advantage of OSLO

- OSLO works like to window's program. It is convenient for you to use the mouse and enter the data.
- OSLO also provides the command interface. Users can choose both windows interface and command interface by convenience.
- The analyzed data output could be in graphic type or in text type.
- In optimization and tolerance analyses, users could employ the default error function or create user-defined error function.
- OSLO provides global optimization to find the best solutions of a system.

The interface of OSLO

Surface spreadsheet

Command input area



Graphic window

Text window

Surface data spreadsheet

Gen	Setup	Wavelengths	Variables	Draw On	Group	Notes
Lens: Demo Triplet 50mm f/4 20deg						Ef1 50.000541
Ent beam radius 6.250000						Field angle 20.000000
Primary wavln 0.587560						
SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL	
OBJ	0.000000	1.0000e+20	3.6897e+19	AIR		
1	21.250000	2.000000	6.500000	SK16	C	
2	-158.650000	6.000000	6.500000	AIR		
3	-20.250000	1.000000	5.000000	F4	C	
AST	19.300000	6.000000	5.000000	AIR		
5	141.250000	2.000000	6.500000	SK16	C	
6	-17.285000	42.950000	5.500000	AIR		
IMS	8.000000	0.000000	18.170326	S		

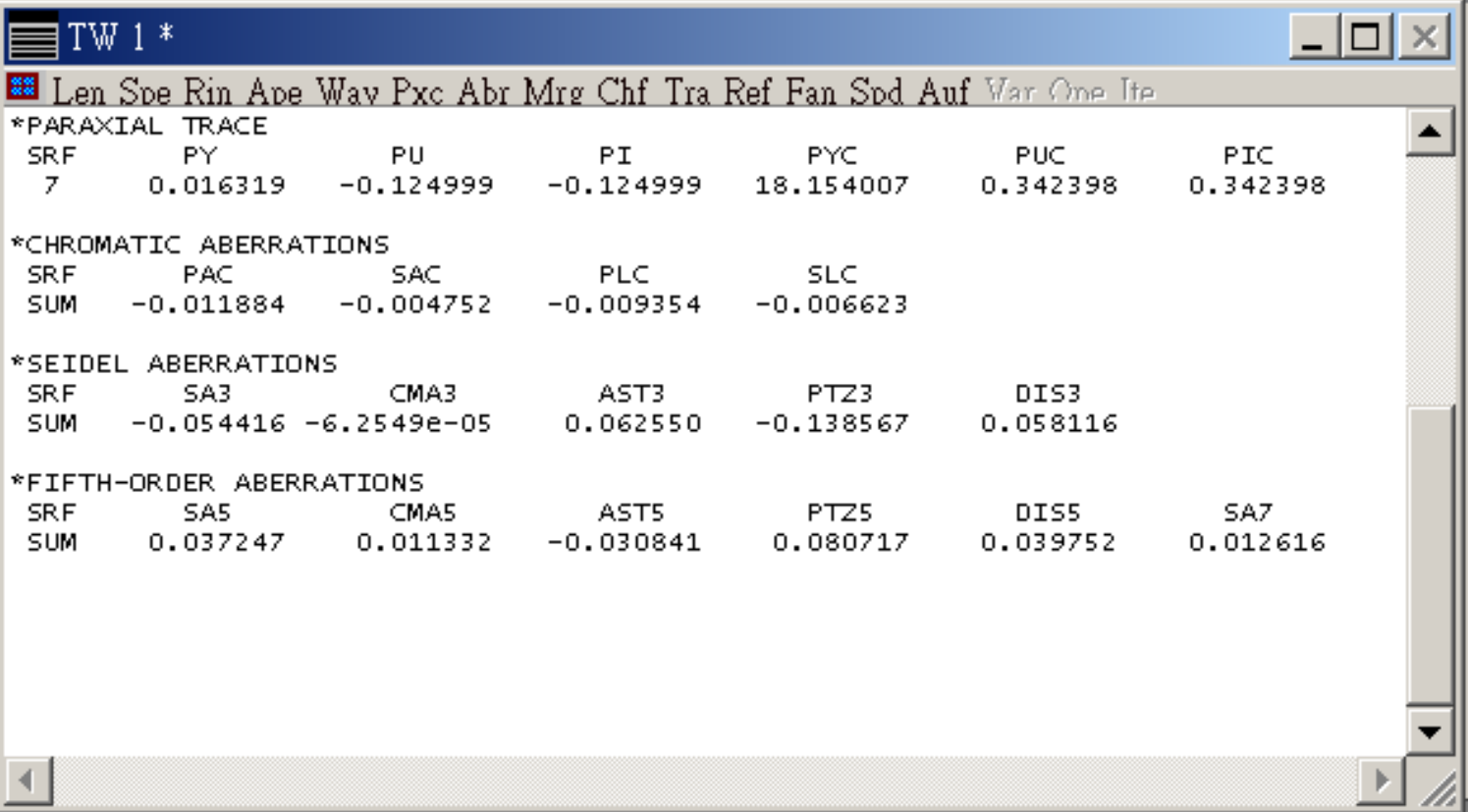
Curvature
radius

thickness

Aperture radius

Glass material

Text output



TW 1 *

Len Spe Rin Ape Wav Pxc Abr Mrg Chf Tra Ref Fan Sod Auf Var One Ite

*PARAXIAL TRACE

SRF	PY	PU	PI	PYC	PUC	PIC
7	0.016319	-0.124999	-0.124999	18.154007	0.342398	0.342398

*CHROMATIC ABERRATIONS

SRF	PAC	SAC	PLC	SLC
SUM	-0.011884	-0.004752	-0.009354	-0.006623

*SEIDEL ABERRATIONS

SRF	SA3	CMA3	AST3	PTZ3	DIS3
SUM	-0.054416	-6.2549e-05	0.062550	-0.138567	0.058116

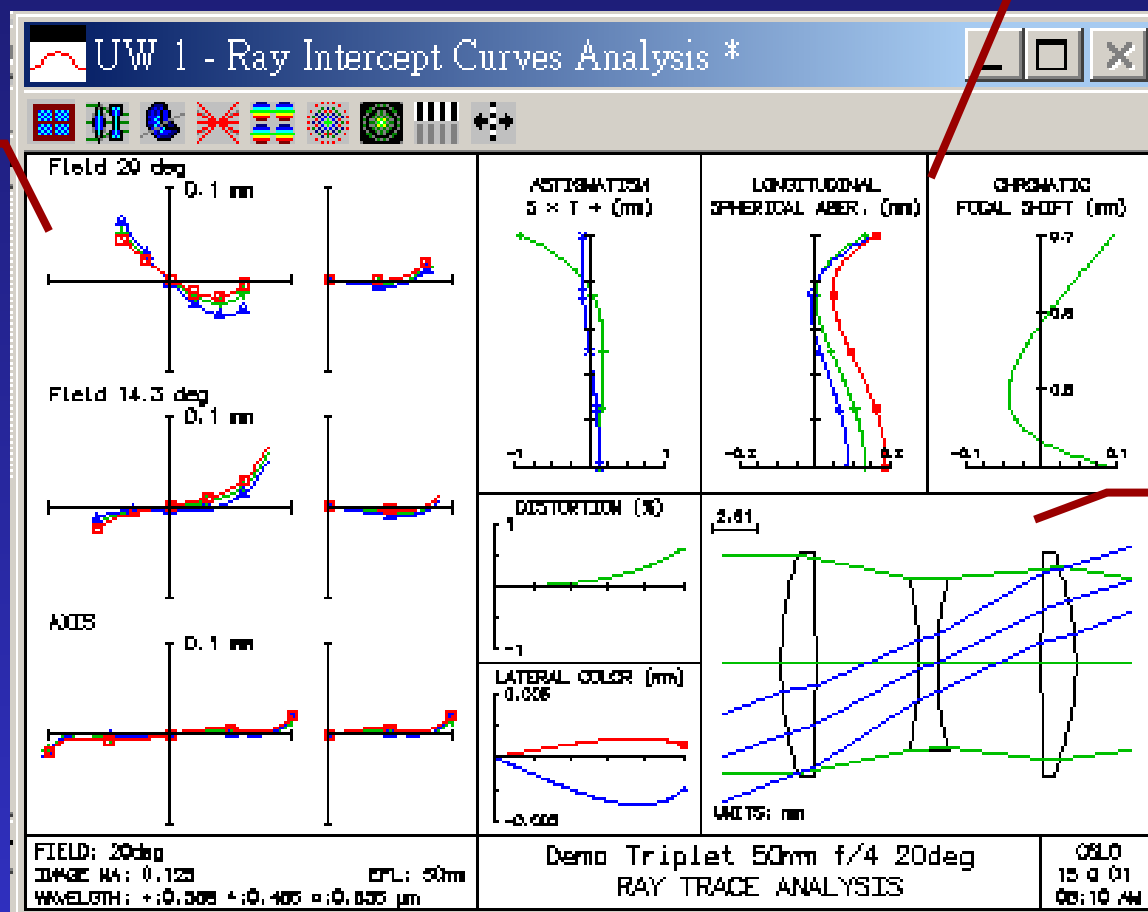
*FIFTH-ORDER ABERRATIONS

SRF	SA5	CMA5	AST5	PTZ5	DIS5	SA7
SUM	0.037247	0.011332	-0.030841	0.080717	0.039752	0.012616

Graphic Output

Ray intercept
curve

Aberration
plots



System
layout

What could be designed by OSLO?

- Standard geometrical optical lens system
- Standard reflected system
- Aspherical lens system
- Non-sequential lens array system
- Diffraction optical element

The limitation of OSLO

- It could not simulate physical optics.
- It could not do stray-light analysis of a system.
- It could not simulate complex light sources.

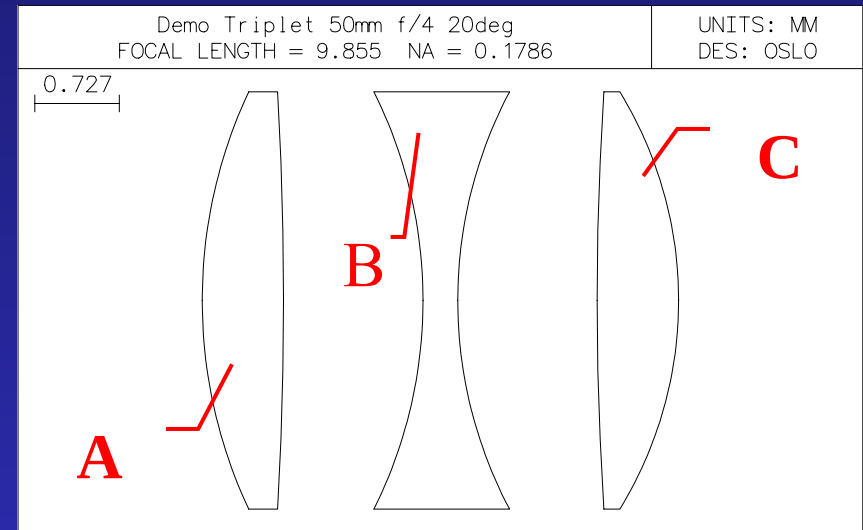
Basic fundamental of OSLO

-
- Ray tracing
 - Image quality analysis
 - Aberration analysis
 - Image evaluation
 - Spot diagram, MTF, PSF etc
 - Optimization
 - Tolerance

Example 1

Cooke triple

- Focal length: 10mm
- $f/\# : f/2.8$
- Half field angle : 20°
- Aperture radius : 1.8mm
- materials:
 - Lens A and Lens C : SK16
 - Lens B : F4
- Working wavelengths
 - main : $0.5876 \mu\text{m}$
 - $0.4861 \mu\text{m}$
 - $0.6563 \mu\text{m}$



The procedure of optical system design

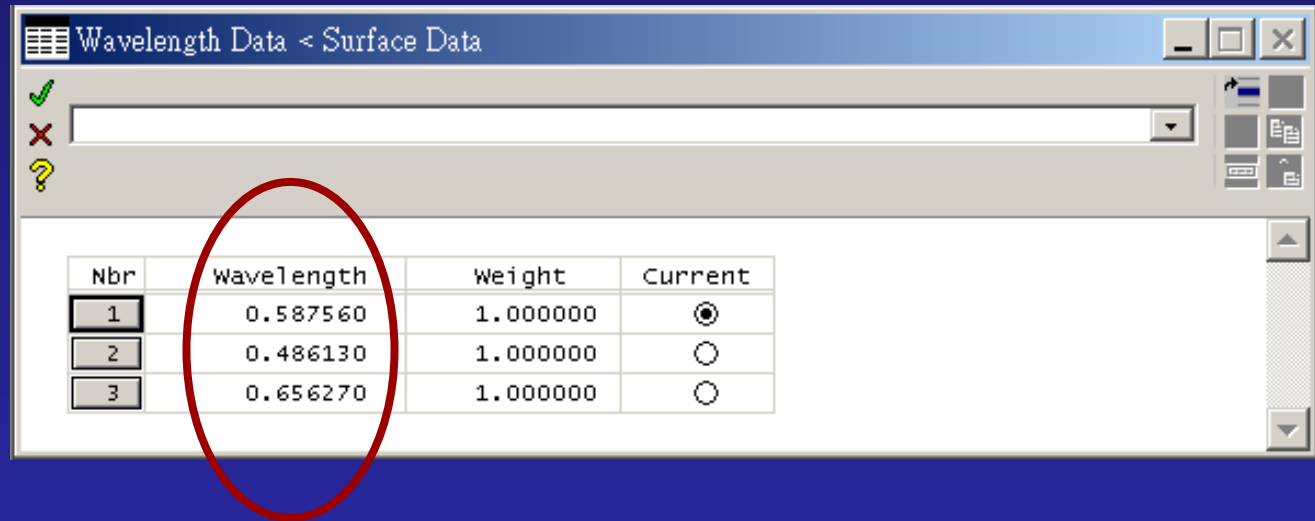
1. System data entry
2. Ray tracing
3. Checking optical performance
4. Optimization
5. Tolerance

Data entry

- System parameters
 - Wavelengths
 - Lens parameters
 - Curvature radius
 - Thickness
 - Aperture radius
 - Glass materials
 - Field angle
 - Paraxial parameters
 - Beam radius
 - $f/\#$

Data entry – wavelength and field angle

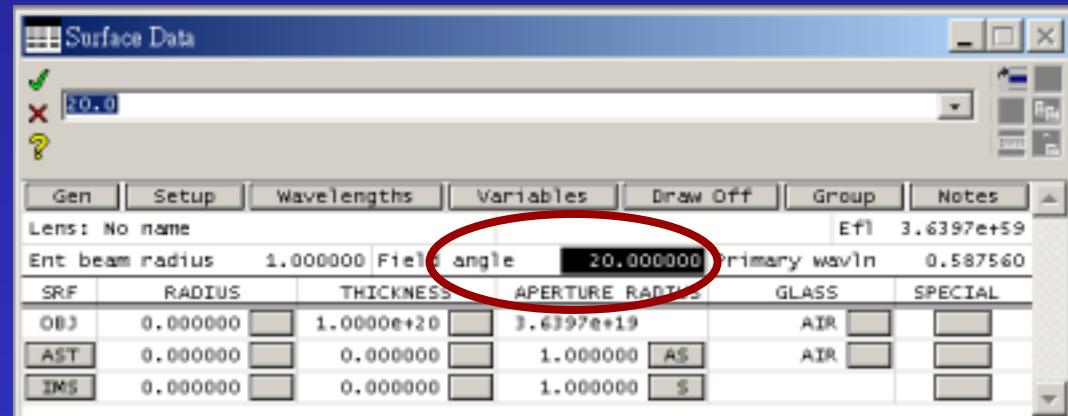
- Wavelength



Wavelength Data < Surface Data

Nbr	Wavelength	Weight	Current
1	0.587560	1.000000	☒
2	0.486130	1.000000	☐
3	0.656270	1.000000	☐

- Field angle



Surface Data

Gen Setup Wavelengths Variables Draw Off Group Notes

Lens: No name Efl 3.6397e+59

Ent beam radius 1.000000 Field angle 20.000000 primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+20	3.6397e+19	AIR	
AST	0.000000	0.000000	1.000000 AS	AIR	
IMS	0.000000	0.000000	1.000000 S		

Data entry – lens parameters

- When you enter the surface data, it is better to move from right to left :glass, aperture radius, thickness, finally radius.

Surface Data

Command: Triplet 10mm f/2.8 20deg

Gen Setup Wavelength Field Points Variables Draw On Group Notes

Lens: Triplet 10mm f/2.8 20deg Zoom 1 of 1 Efl 9.854505

Ent beam radius 1.249986 Field angle 20.000000 Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	2.0000e+19	7.2793e+18	AIR	
1	4.249954	0.700000	1.800000 K	SK16 C	
2	-31.729657	1.199987	1.800000 P	AIR	
3	-4.049956	0.300000	1.800000	F4 C	
AST	3.859958	1.199987	1.800000 A	AIR	
5	28.249694	0.700000	1.800000	SK16 C	
6	-3.456963	8.589907	1.800000 K	AIR	
IMS	0.000000	0.000000	3.785272 S		

Data entry – paraxial parameters

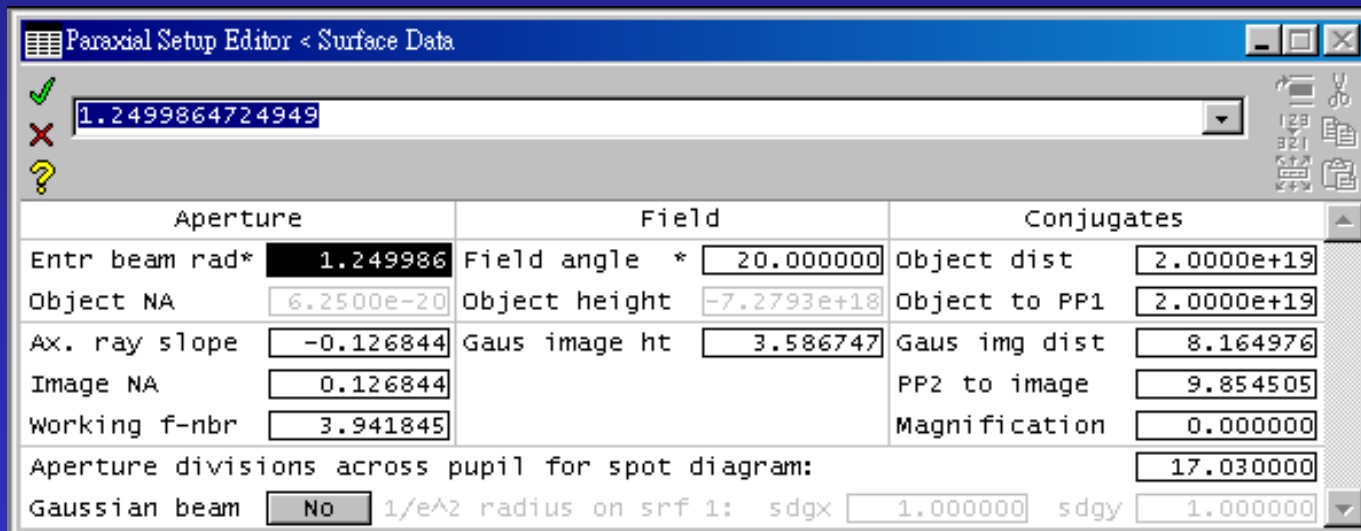
- We should enter 1.78571 in entrance beam radius field, since the f-number must set in 2.8.



$$f / \# = \frac{f}{D}$$

D=entrance beam radius

f=focal length



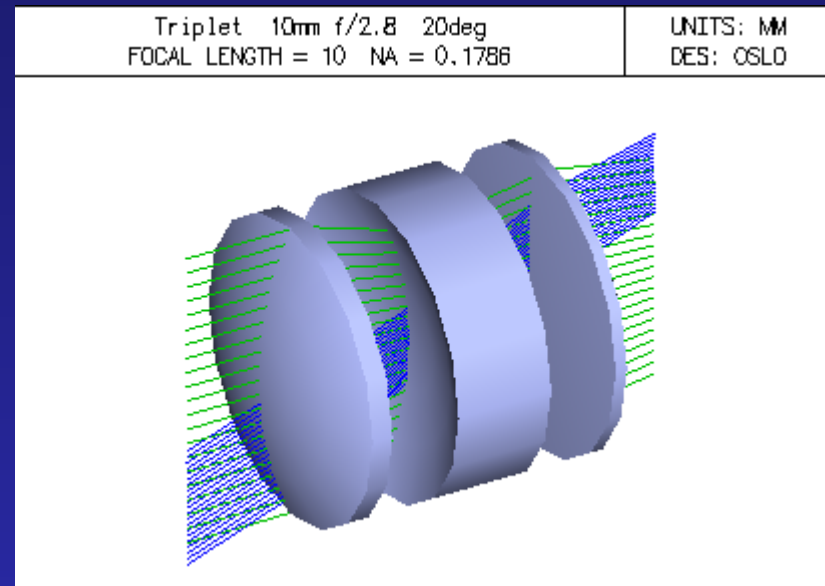
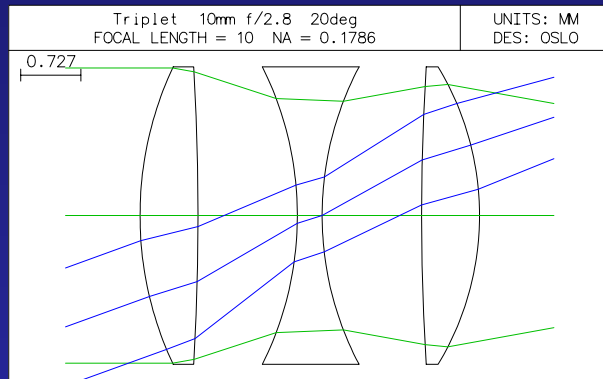
Paraxial Setup Editor < Surface Data

1.2499864724949

Aperture		Field		Conjugates		
Entr beam rad*	1.249986	Field angle *	20.000000	Object dist	2.0000e+19	
Object NA	6.2500e-20	Object height	-7.2793e+18	Object to PP1	2.0000e+19	
Ax. ray slope	-0.126844	Gaus image ht	3.586747	Gaus img dist	8.164976	
Image NA	0.126844			PP2 to image	9.854505	
Working f-nbr	3.941845			Magnification	0.000000	
Aperture divisions across pupil for spot diagram:					17.030000	
Gaussian beam	No	1/e^2 radius on srf 1: sdgx		1.000000	sdgy	1.000000

Checking the feature

- Graphic output



- Text output

```
*LENS DATA
Triplet 10mm f/2.8 20deg
SRF      RADIUS      THICKNESS  APERTURE RADIUS  GLASS  SPE  NOTE
OBJ      --          2.0000e+19  7.2793e+18      AIR
1         4.249954      0.700000    1.800000 K      SK16  C
2        -31.729657      1.199987    1.800000 P      AIR
3         -4.049956      0.300000    1.800000        F4  C
AST        3.859958      1.199987    1.800000 A      AIR
5         28.249694      0.700000    1.800000      SK16  C
6         -3.491631 S      8.589907    1.800000 K      AIR
IMS      --          --          3.798090 S
```

Ray trace

- Paraxial ray tracing
 - Command : “pxt all”
 - The algorithm is YUI method
 - Y: the ray height at surface
 - U: ray slope
 - I: ray angle

$$y' = y + tu$$

$$i = u + yc$$

$$u' = u + \left(\frac{n}{n'} - 1 \right) i$$

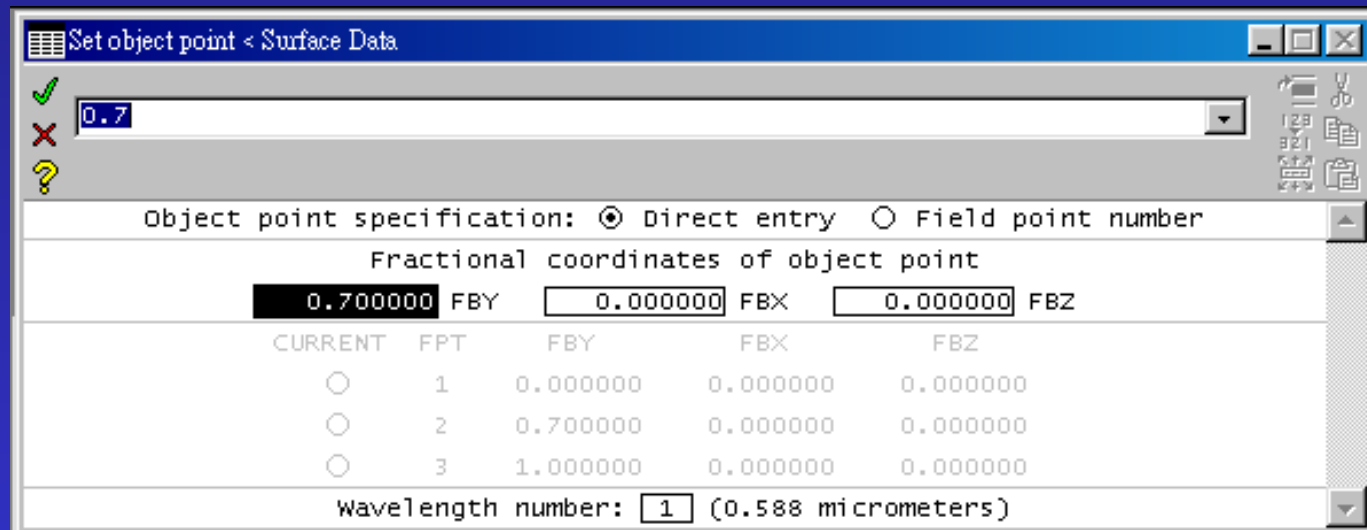
SRF	PY	PU	PI	PYC	PUC	PIC
0	--	8.9286e-20	8.9286e-20	-7.2793e+18	0.363970	0.363970
1	1.785710	-0.160872	0.420172	-0.922982	0.307766	0.146796
2	1.673100	-0.293393	-0.213602	-0.707546	0.512542	0.330065
3	1.321032	-0.057077	-0.619577	-0.092502	0.308339	0.535382
4	1.303909	0.116017	0.280727	-1.1102e-16	0.498459	0.308339
5	1.443128	0.052038	0.167102	0.598144	0.299506	0.519633
6	1.479555	-0.178571	-0.371705	0.807799	0.341789	0.068153
7	-0.054354	-0.178571	-0.178571	3.743737	0.341789	0.341789

Axial rays

Chief rays

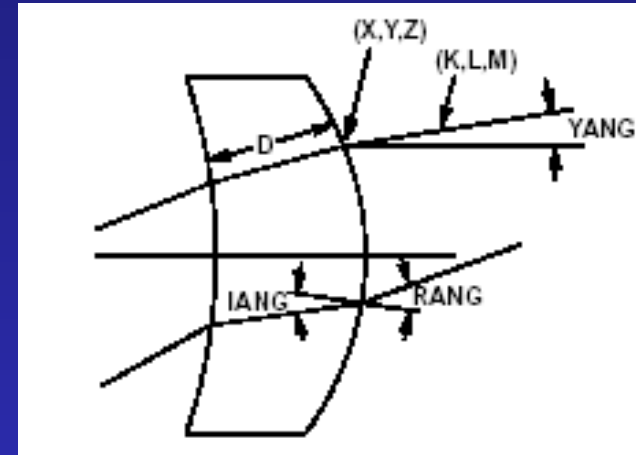
Setting object point

- Using menu :
 - Select “Evaluate >> Single Ray Trace>>Set object point”
- Using command :
 - set_object_point (FBY) (FBX) (FBZ) (FYRF) (FXRF)
 - FBY,FBX,FBZ : object point fractional coordinates
 - FYRF,FXRF : aperture-stop coordinates of a reference ray.



Ray trace

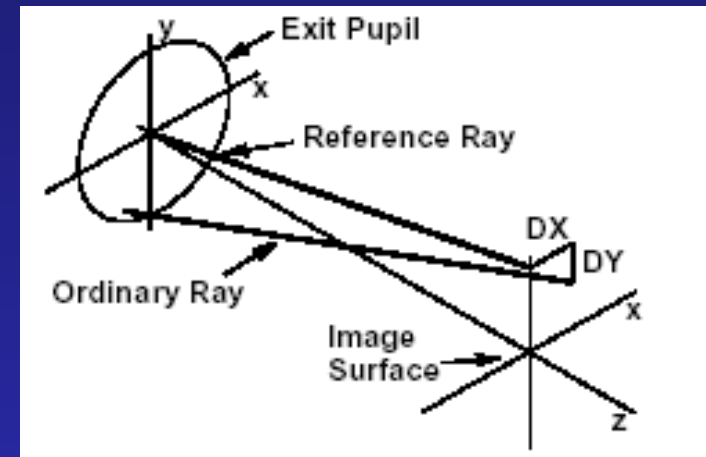
- Single ray trace
 - It shows the trajectory of a single Lagrangian (ordinary) ray through an optical system.
 - Evaluate >> Single Ray Trace
 - K,L,M : direction cosine
 - IANG, RANG :incident and refraction angle



*TRACE RAY	- LOCAL COORDS -	FBY	1.00, FBX	0.00, FBZ	0.00		
SRF	Y/L	X/K	Z/M	YANG/IANG	XANG/RANG	D/DPL	
7	3.778731	--	--	18.607615	--	9.174849	
	0.319085	--	0.947726	18.607615	18.607615	14.210446	
PUPIL	FY	FX	RAY AIMING			OPD	
	--	--	CENTRAL REF RAY			--	

Ray trace

- Ray fans
 - FY: fractional coordinates in object space
 - DX, DY, DZ: image displacement
 - DYA, DXA : the differences in ray slope between the ray and reference ray.
 - OPD: optical path difference.



*TRACE FAN - FBY 1.00, FBX 0.00, FBZ 0.00

RAY	FY	FRAC RFS	DYA	DXA	DY	DX	DZ	OPD	DMD
1	1.000000	0.689575	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20
2	0.500000	0.327809	-0.081239	--	-0.021304	--	--	1.398099	0.422897
3	--	--	--	--	--	--	--	--	--
4	-0.500000	-0.302660	0.083840	--	0.016727	--	--	1.099659	0.722299
5	-1.000000	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20	1.0000e+20

Ray trace

- Ray-intercept curves
 - Select “Ray fans >> single field point”
 - These curves are graphical plots of ray fans.
 - The data represents image space displacements as a function of object-space fractional coordinates.

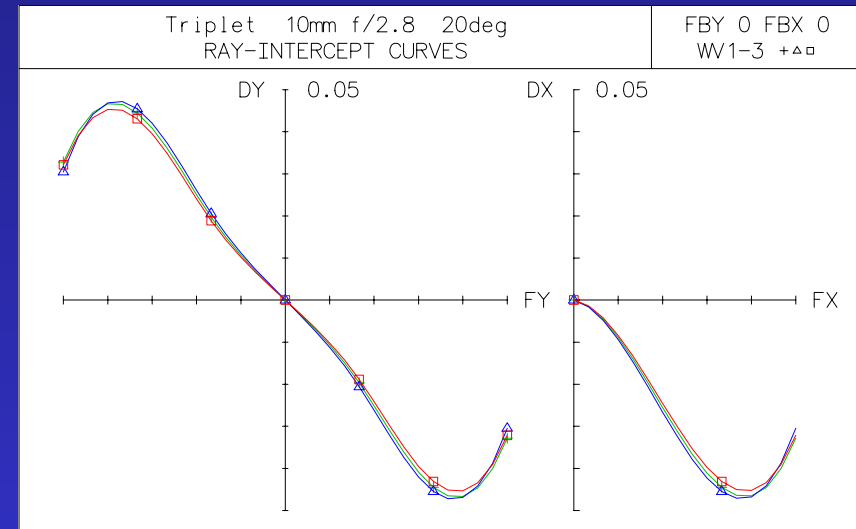


Image quality analysis

- Aberration
 - Spherical aberration
 - Chromatic aberration
 - Astigmatism
 - Distortion
- Spot diagram
- MTF
- SPF
- Energy distribution

Aberration

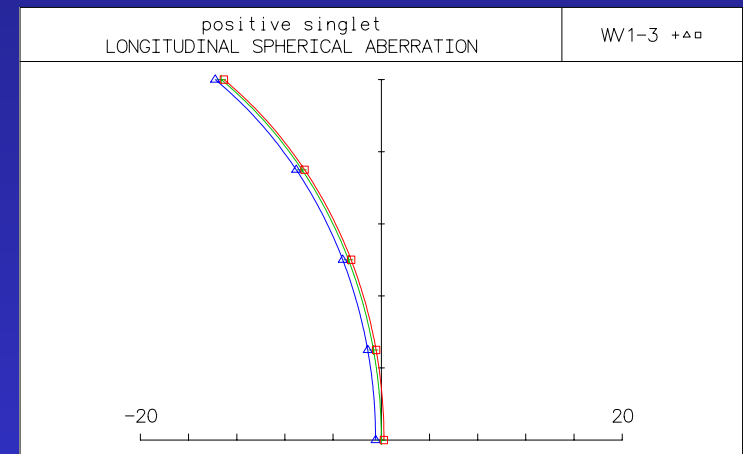
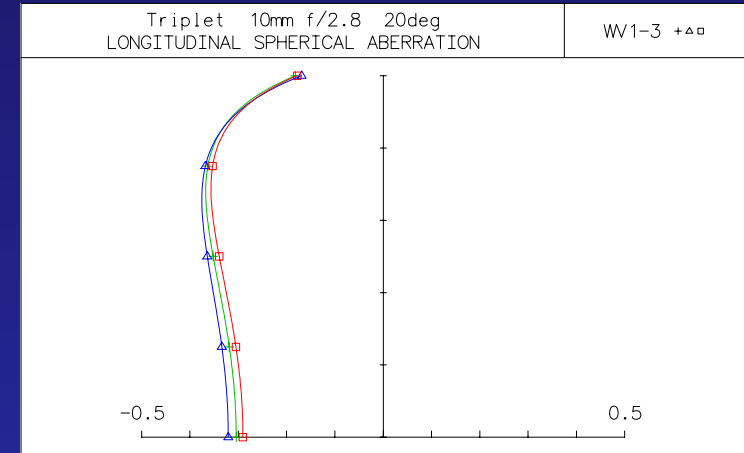
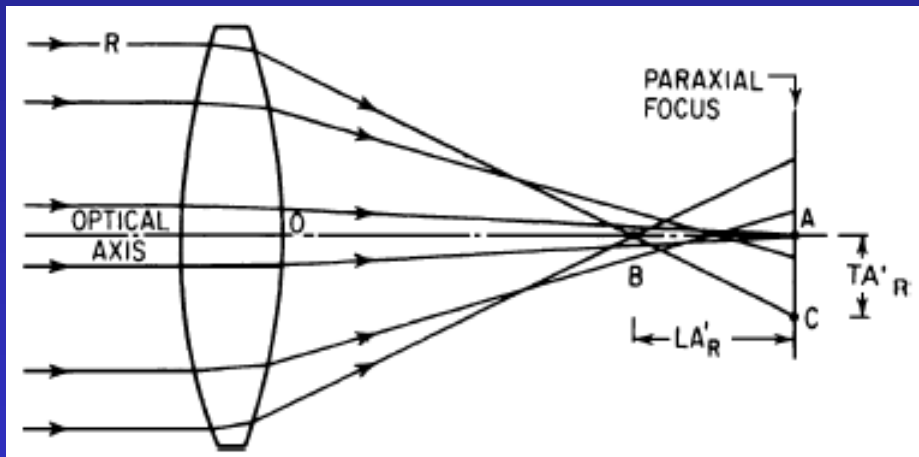
- Spherical aberration

- Longitudinal spherical aberration

$$LA_B = L - l$$

- Lateral spherical aberration

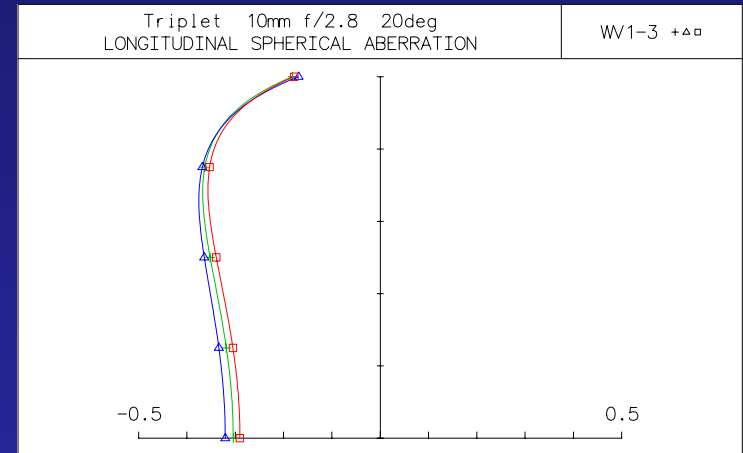
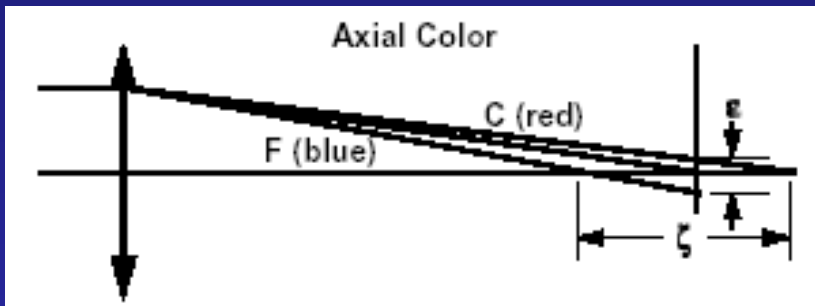
$$TA_B = LA_B \tan U_B = (L - l) \tan U_B$$



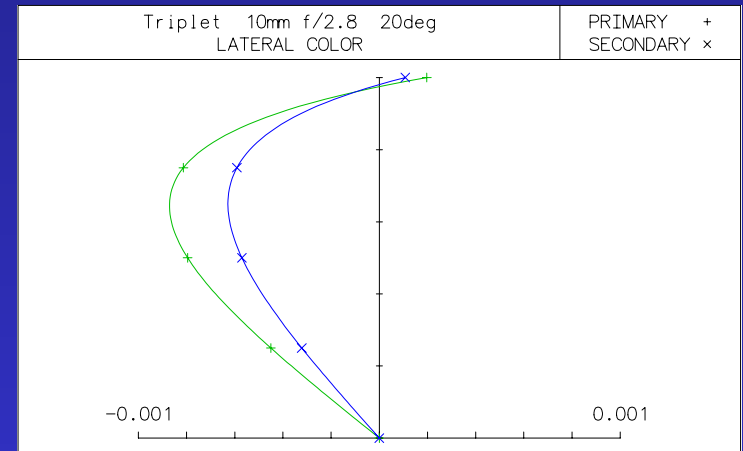
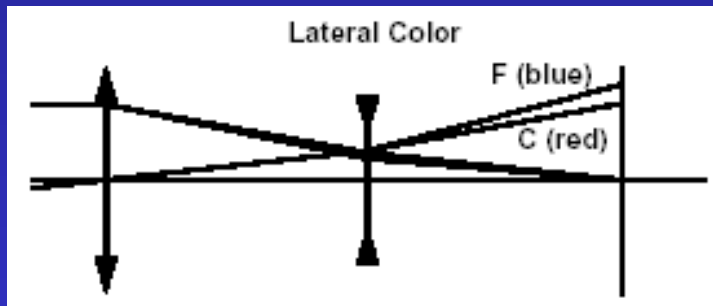
Aberration

- Chromatic spherical aberration

- Longitudinal chromatic aberration

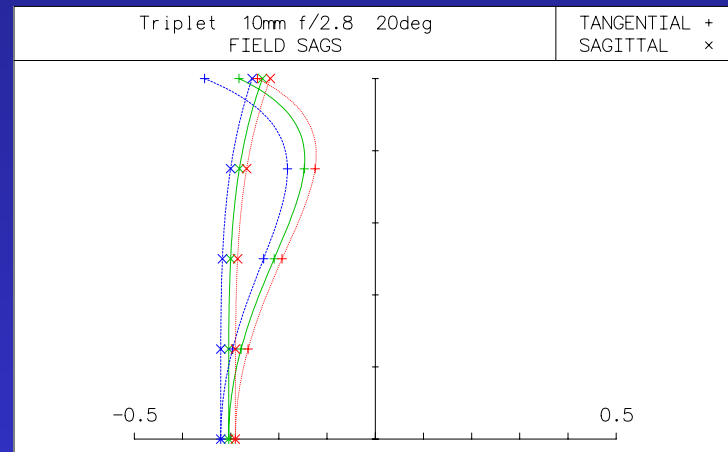
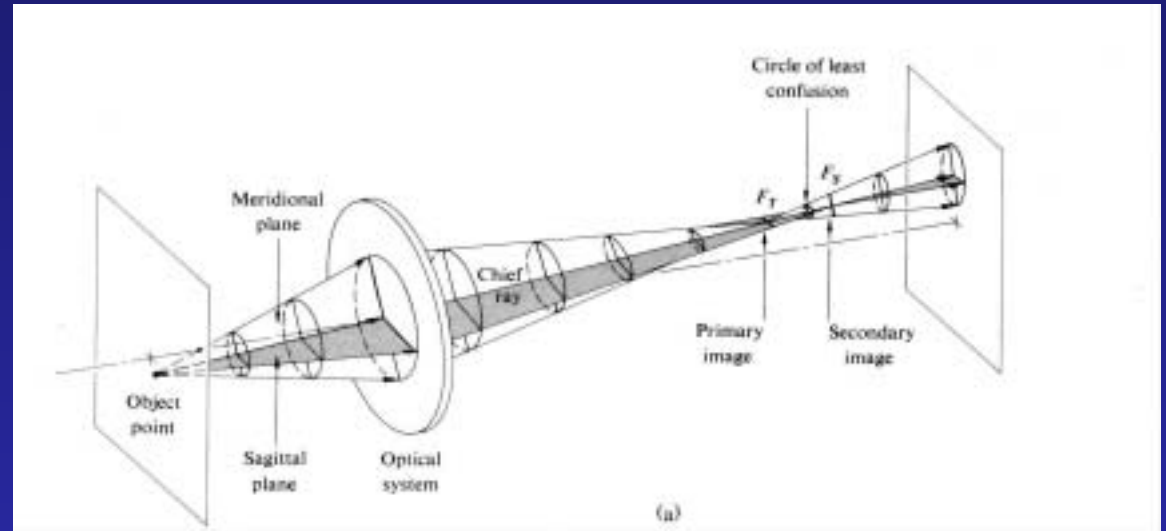
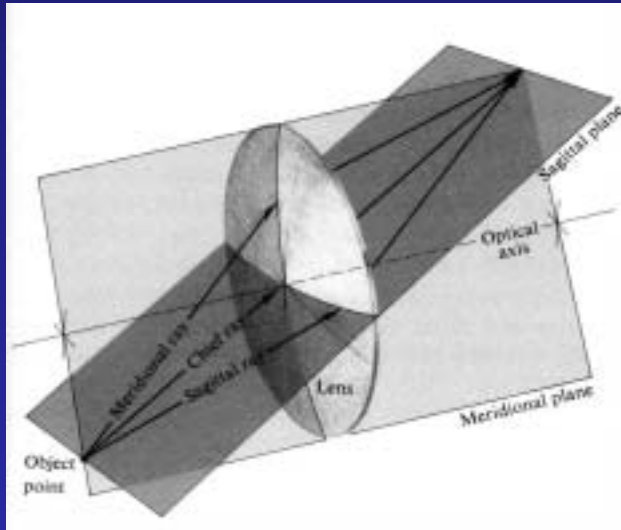


- Lateral color



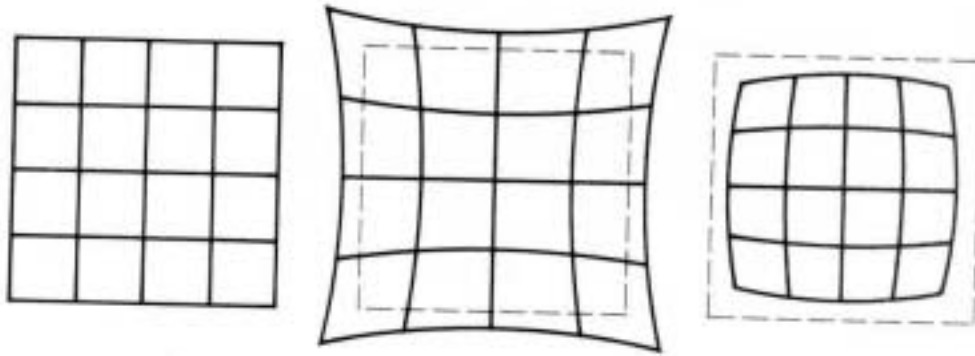
Aberration

- Astigmatism

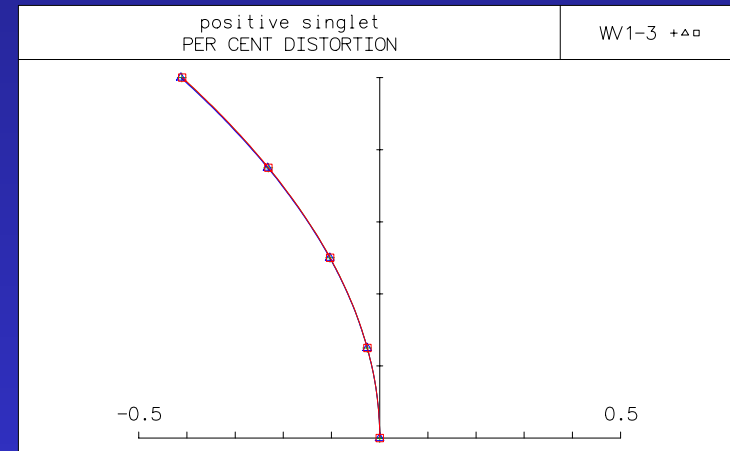
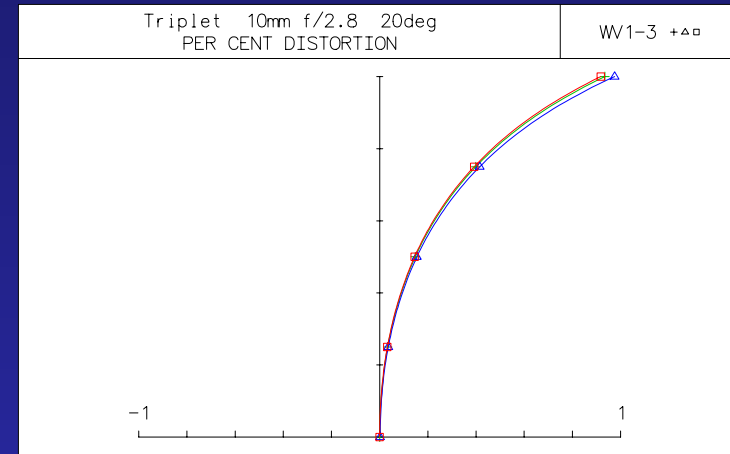


Aberration

- Distortion

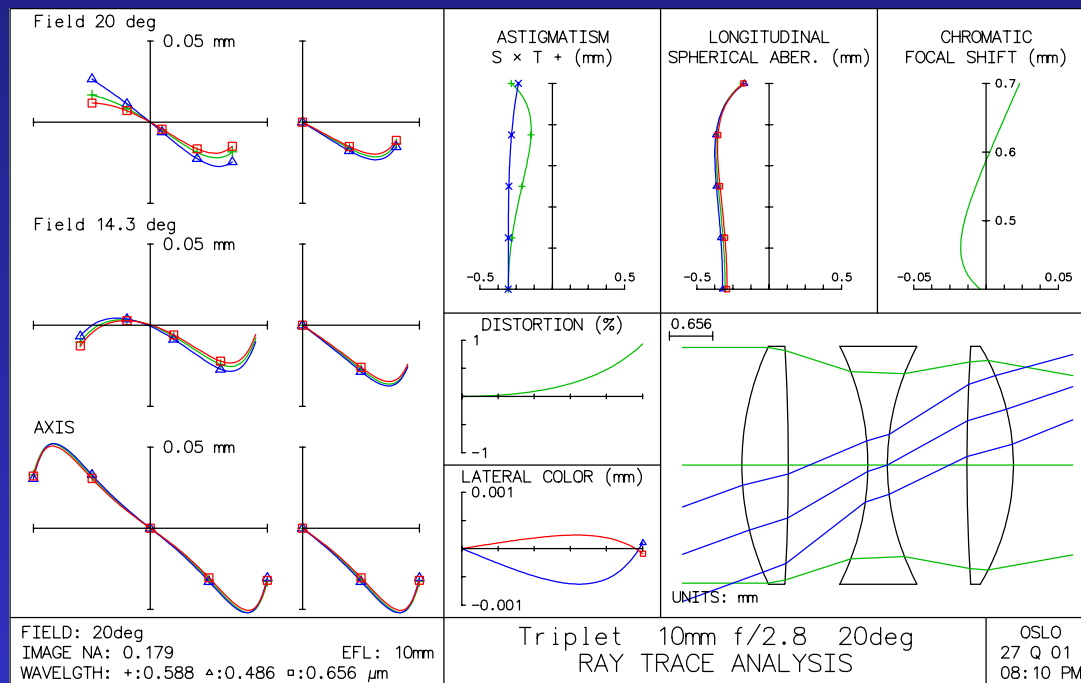


- $\text{distortion} < 0$: barrel distortion
- $\text{distortion} > 0$: pincushion distortion



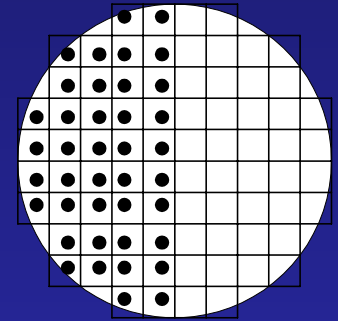
Report graphs of Ray analysis

- This report graph includes the ray intercept curves, spherical aberration plot, astigmatism plot, chromatic focal shift plot, distortion plot, and lateral color plot.



Spot diagram

- A collection of ray data resulting from tracing a large number of rays from a single object point through the aperture of the lens.
- In OSLO, the rays that trace for a spot diagram is distributed in a *square grid* in *entrance pupil*. The parameter is set in the Setup spreadsheet.



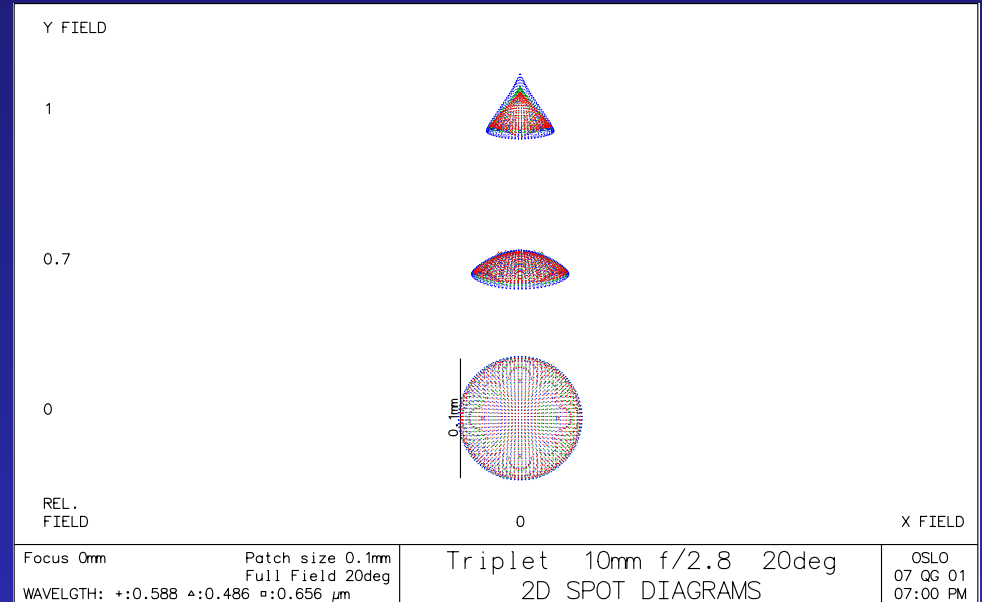
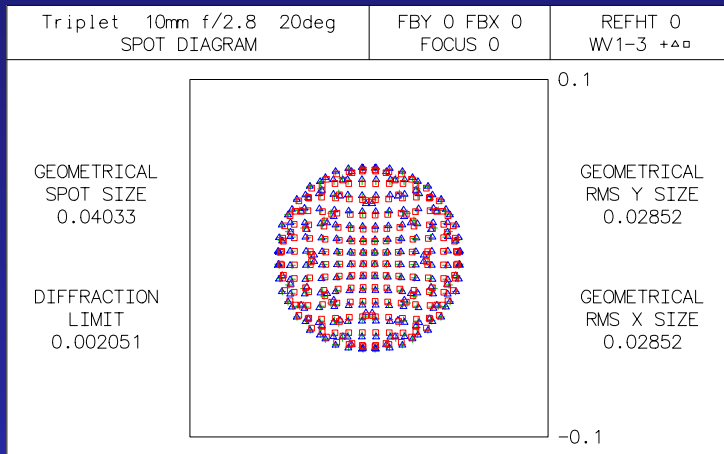
Paraxial Setup Editor < Surface Data

17.03

Aperture		Field		Conjugates	
Entr beam rad*	1.785710	Field angle *	20.000000	Object dist	2.0000e+19
Object NA	8.9286e-20	Object height	-7.2793e+18	Object to PP1	2.0000e+19
Ax. ray slope	-0.178571	Gaus image ht	3.639702	Gaus img dist	8.285526
Image NA	0.178571			PP2 to image	10.000000
Working f-nbr	2.800007			Magnification	0.000000
Aperture divisions across pupil for spot diagram:					17.030000
Gaussian beam	No	1/e^2 radius on srf 1:	sdgx 1.000000	sdgy	1.000000

Spot diagram

- Graphic output



Spot diagram

- Text output
 - Using “Evaluate >> Spot Diagram >> Spot Size Analysis”

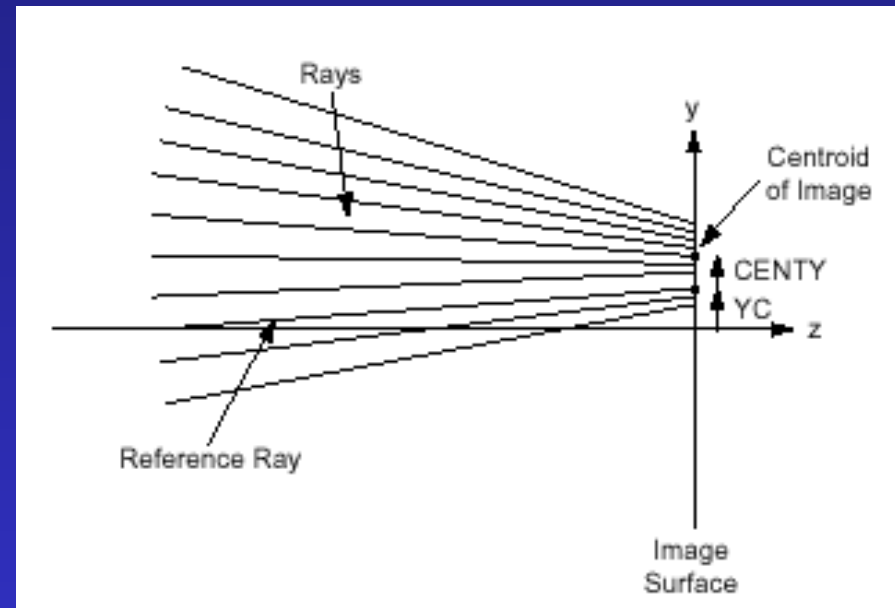
```
*SPOT SIZES
GEO RMS Y    GEO RMS X    GEO RMS R    DIFFR LIMIT    CENTY    CENTX
0.028518     0.028518     0.040330     0.002051       --       --
```

σ_x

σ_y

σ_r

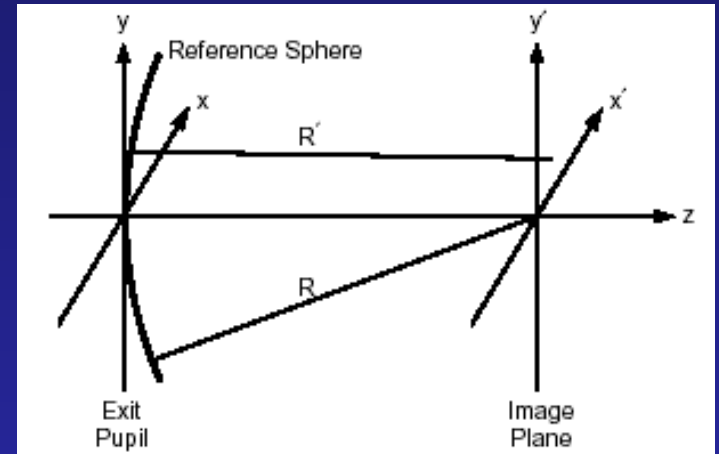
$$\sigma_x^2 = \frac{1}{W} \sum_{i=1}^n w_i (DX_i - \langle x \rangle)^2$$
$$\sigma_y^2 = \frac{1}{W} \sum_{i=1}^n w_i (DY_i - \langle y \rangle)^2$$
$$\sigma_r = \sqrt{\sigma_x^2 + \sigma_y^2}$$



PSF

- Full name : Point Spread Function
- The diffraction image of a point object.
 - The diffraction amplitude

$$U(x', y') = \frac{1}{\lambda} \iint_A P(x, y) \frac{\exp(-ikR')}{R'} dA$$



- $P(x, y)$: complex pupil function
- The usual definition of point spread function

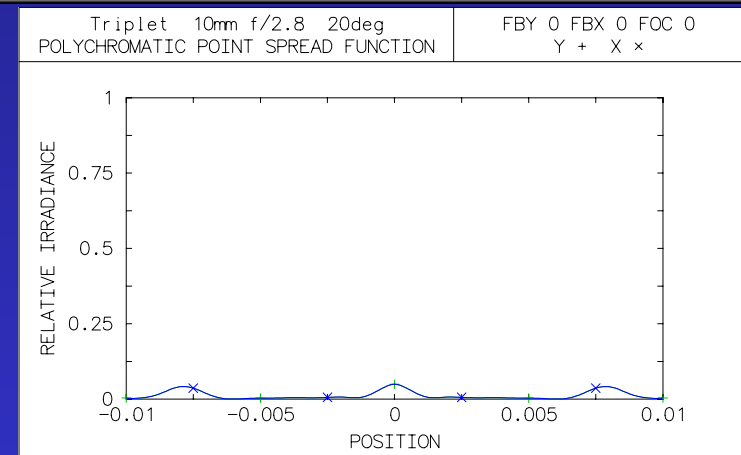
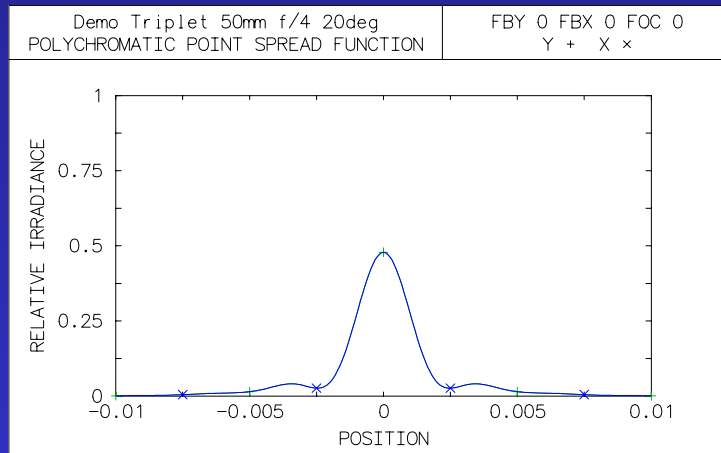
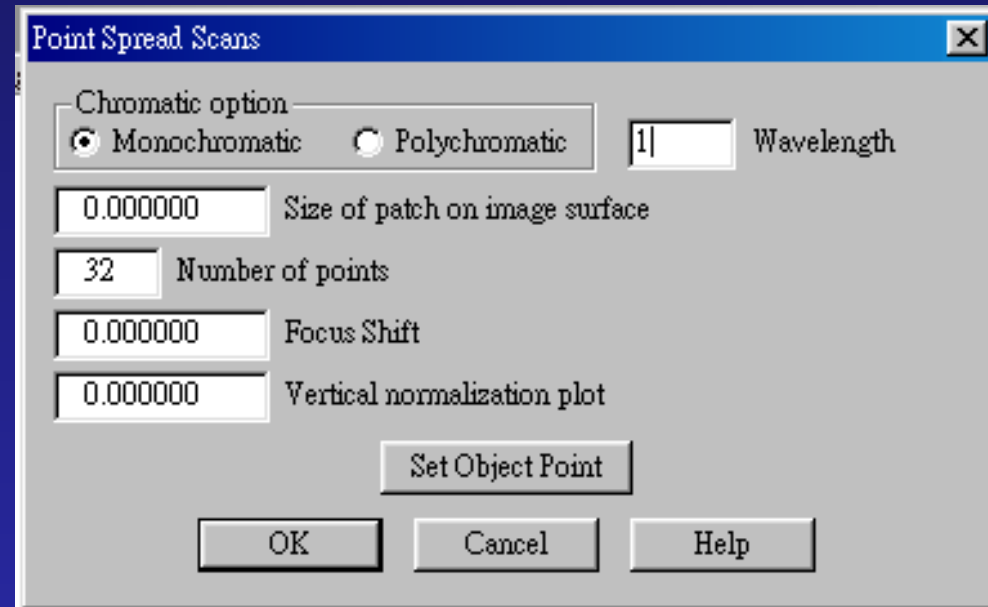
$$PSF(x', y') = |U(x', y')|^2$$

- The airy disk = diffraction limit

$$r'_{airy} = \frac{0.61\lambda_0}{NA}$$

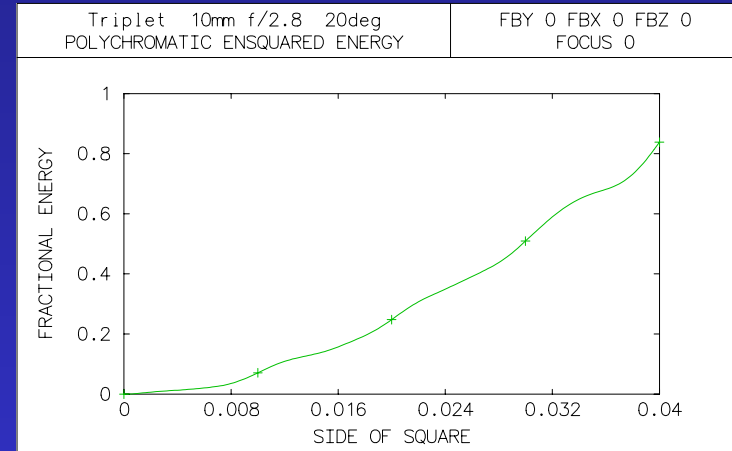
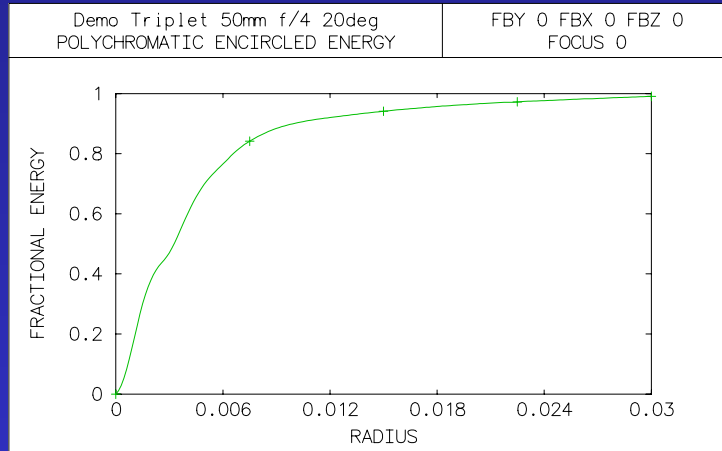
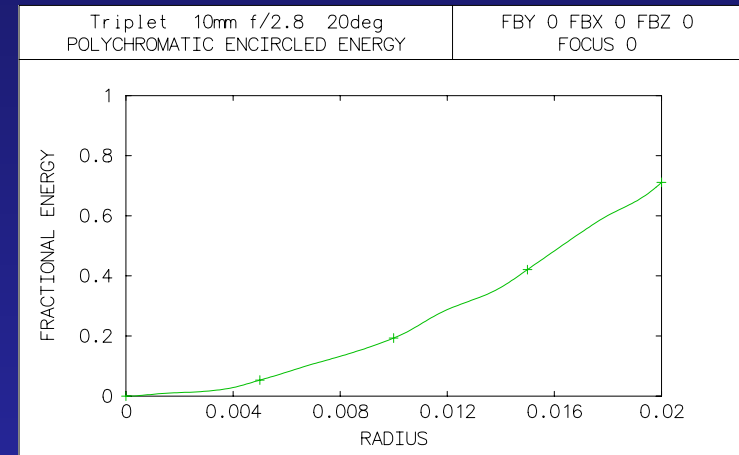
PSF

- Using “Evaluate >> Spread Function >> Plot PSF Scans “



Energy distribution

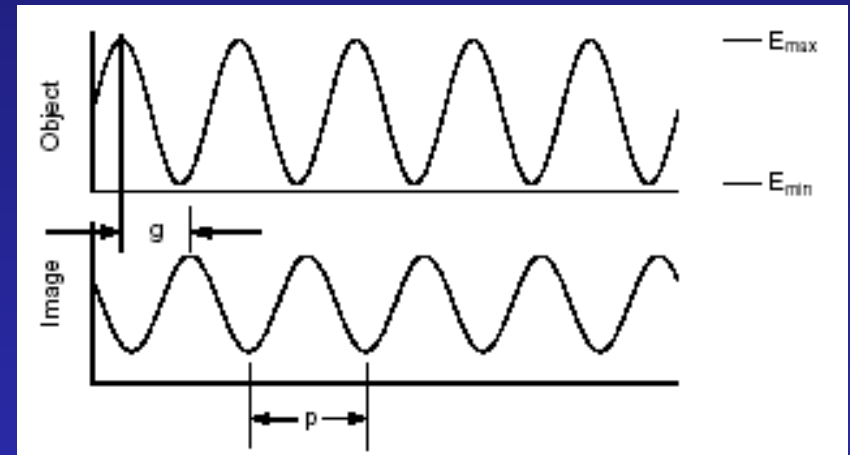
- It is representing how much of the total energy in the point image is contained within a circle or square of size which is given.



MTF (modulation transfer function)

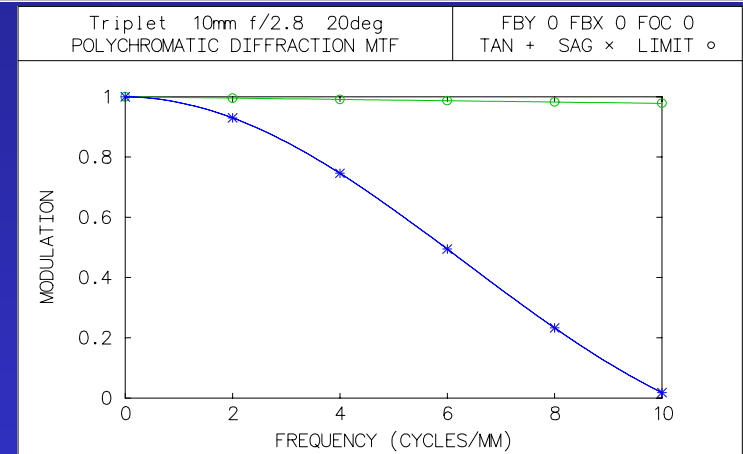
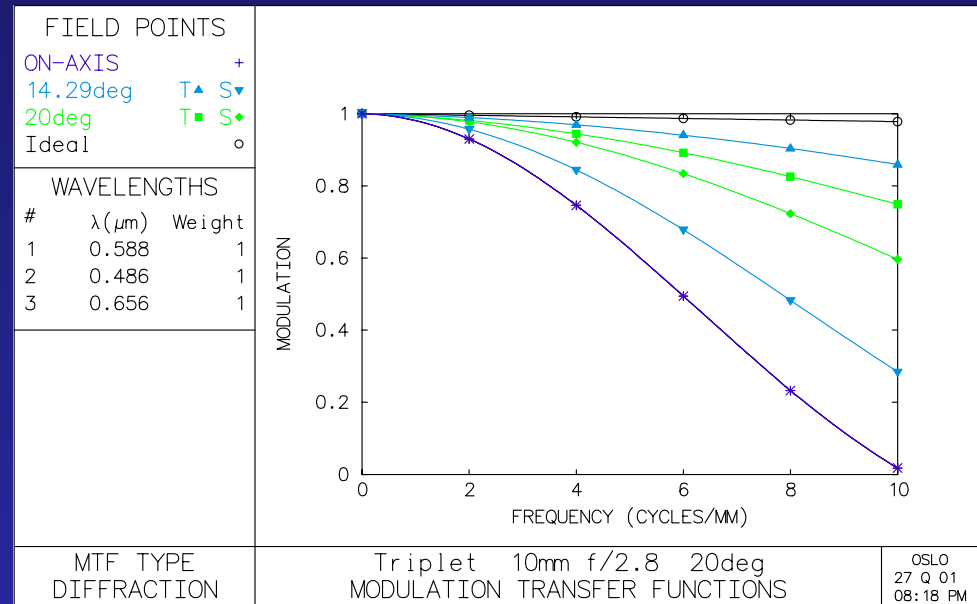
- The OTF (optical transfer function) is a measure of the accuracy with which different frequency components in the object are reproduced in the image
- The algorithm of MTF and PTF
 - The modulation
$$M = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}}$$
 - MTF, PTF
$$MTF = \frac{M_{\text{image}}}{M_{\text{object}}}$$
$$PTF = 2\pi \frac{g}{p} = 2\pi g \nu$$
- The object irradiance distribution with Fourier spectrum $O(\nu_x, \nu_y)$ and the Fourier spectrum of the image $I(\nu_x, \nu_y)$ have the form :

$$I(\nu_x, \nu_y) = OTF(\nu_x, \nu_y) O(\nu_x, \nu_y)$$

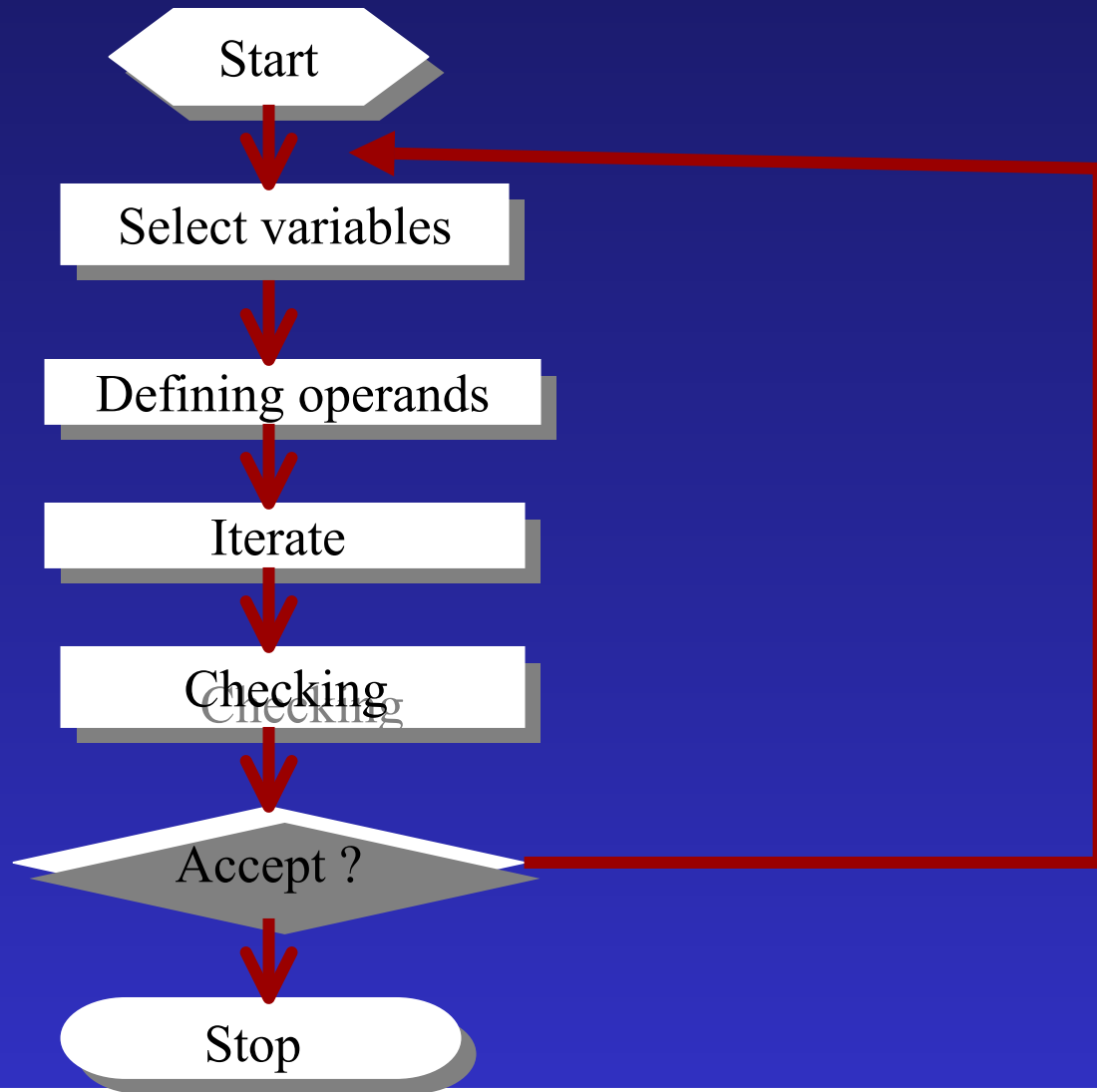


MTF

- We can choose *through-focus MTF* or *through-frequency MTF* in *Calculate optical transfer function* dialog.
- Using “Transfer Function >> Print/Plot OTF “



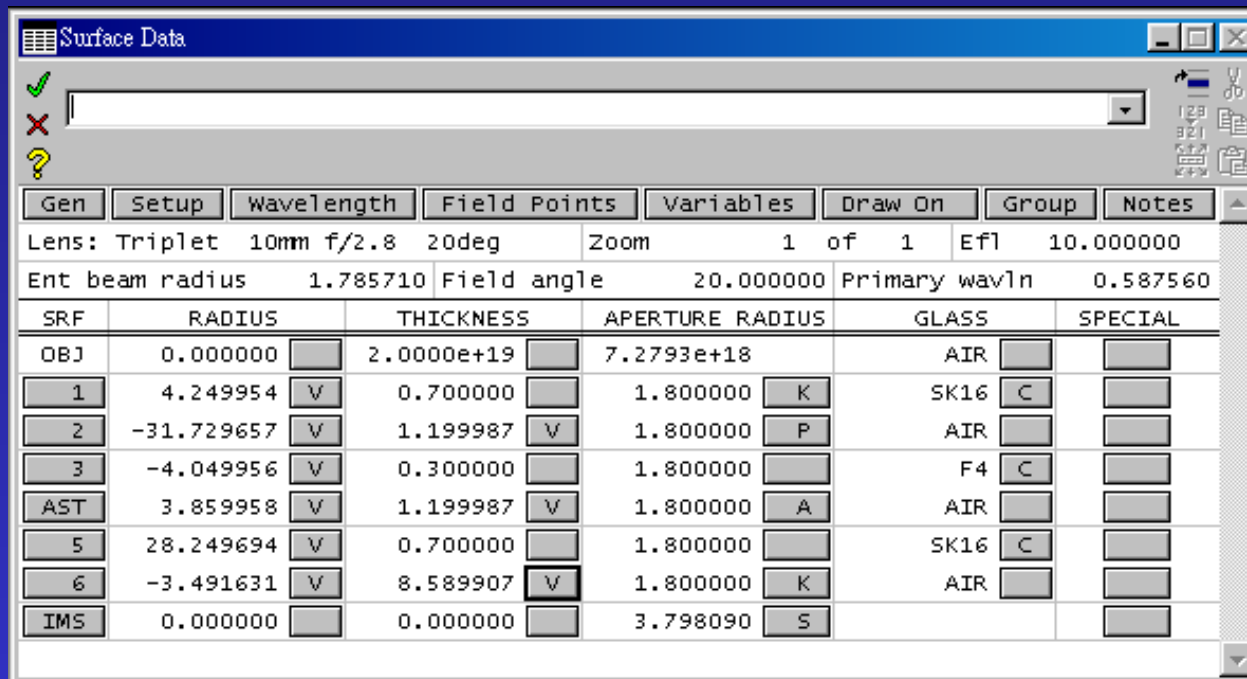
Optimization



Optimization – curvature radius and thickness

- Step 1: Setting variables

- First, we would like to optimize the curvature radius and the thickness of the system.
- All the curvature radius are defined as variables.
- Because the element thickness could not be changed, the thickness of Srf 2, Srf 4 and Srf 6 are defined as variables.



Optimization – curvature radius and thickness

- Step 2: Setting operands
 - Optimize >> Create Error Function
>> GENI ray aberration
 - Using the GENI error function is the most convenient method.
 - GENI error function is designed to handle system of moderate complexity, such as camera lenses and other systems having three to eight elements.
 - Click the “Ope” button in the text window to show all the operands been defined.

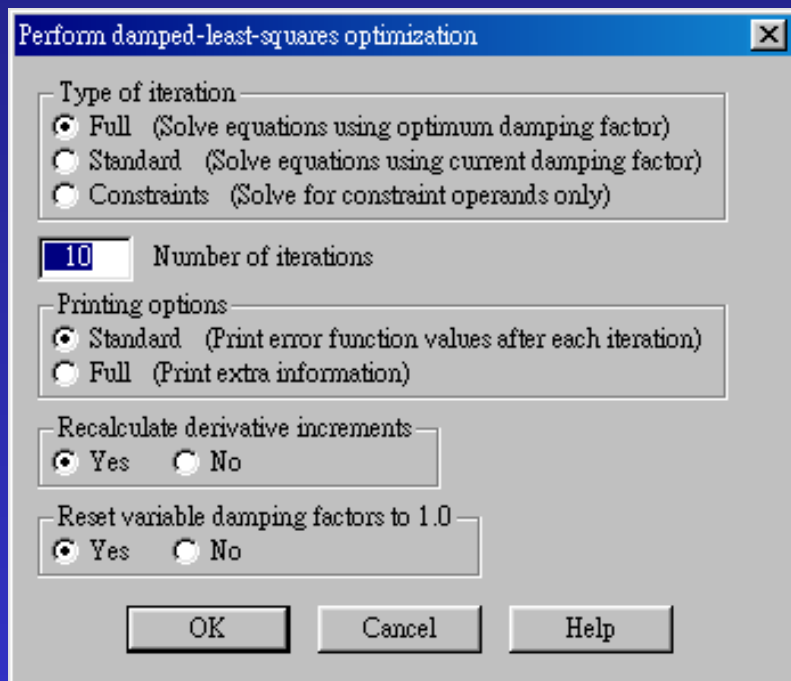
*OPERANDS						
OP	MODE	WGT	NAME	VALUE	%CNTRB	DEFINITION
O 9	M	1.000000	Fnb diff	2.7756e-13	0.00	O8/0.0001
O 10	M	1.000000	Focus diff	-2.717685	1.63	DYY(1,1)/O4
O 11	M	1.000000	Axial DY	-4.922100	5.35	DY(1,2)/O1
O 12	M	1.000000	Axial OPD	13.104220	37.92	OPD(1,2)/O6
O 13	M	1.000000	Axial DMD	0.580152	0.07	DMD(1,2)/O6
O 16	M	1.000000	0.7 Dist	0.332837	0.02	O15/O14
O 17	M	1.000000	0.7 YFS	-1.887871	0.79	DYY(2,1)/O2
O 18	M	1.000000	0.7 XFS	-3.633583	2.92	DXX(2,1)/O2
O 19	M	1.000000	0.7 Coma	1.385733	0.42	S2T(2,1)/O7
O 20	M	1.000000	0.7 DY U	-0.427590	0.04	DY(2,2)/O3
O 21	M	1.000000	0.7 OPD U	5.247948	6.08	OPD(2,2)/O6
O 22	M	1.000000	0.7 DMD U	1.291534	0.37	DMD(2,2)/O6
O 23	M	1.000000	0.7 DY L	-3.946480	3.44	DY(2,3)/O3
O 24	M	1.000000	0.7 OPD L	-4.162142	3.83	OPD(2,3)/O6
O 25	M	1.000000	0.7 DMD L	1.372220	0.42	DMD(2,3)/O6
O 26	M	1.000000	0.7 Sag DX	-1.884340	0.78	DX(2,4)/O3
O 27	M	1.000000	0.7 Sag DY	-1.990562	0.88	DY(2,4)/O1
O 28	M	1.000000	.7 Sag OPD	7.098195	11.13	OPD(2,4)/O6
O 31	M	1.000000	1.0 Dist	0.934756	0.19	O30/O29
O 32	M	1.000000	1.0 YFS	-2.354680	1.22	DYY(3,1)/O4
O 33	M	1.000000	1.0 XFS	-6.121129	8.27	DXX(3,1)/O1
O 34	M	1.000000	1.0 Coma	0.484273	0.05	S2T(3,1)/O7
O 35	M	1.000000	1.0 DY U	-0.305858	0.02	DY(3,2)/O5
O 36	M	1.000000	1.0 OPD U	4.056415	3.63	OPD(3,2)/O6
O 37	M	1.000000	1.0 DMD U	1.618839	0.58	DMD(3,2)/O6
O 38	M	1.000000	1.0 DY L	1.089574	0.26	DY(3,3)/O5
O 39	M	1.000000	1.0 OPD L	3.511281	2.72	OPD(3,3)/O6
O 40	M	1.000000	1.0 DMD L	3.406111	2.56	DMD(3,3)/O6
O 41	M	1.000000	1.0 Sag DX	-0.753095	0.13	DX(3,4)/O5
O 42	M	1.000000	1.0 Sag DY	-2.291776	1.16	DY(3,4)/O1
O 43	M	1.000000	1.0 Sag OPD	3.751035	3.11	OPD(3,4)/O6
MIN RMS ERROR:			3.821989			

Optimization – curvature radius and thickness

- Step 3: Executing “iterate”

- Defining numbers of iterates.
 - “Optimize >> Iterate”
 - We can define the numbers of iterate by myself.
 - The default number is 10.

- After executing “iterate”, the value of the error function will be appeared in the text window.

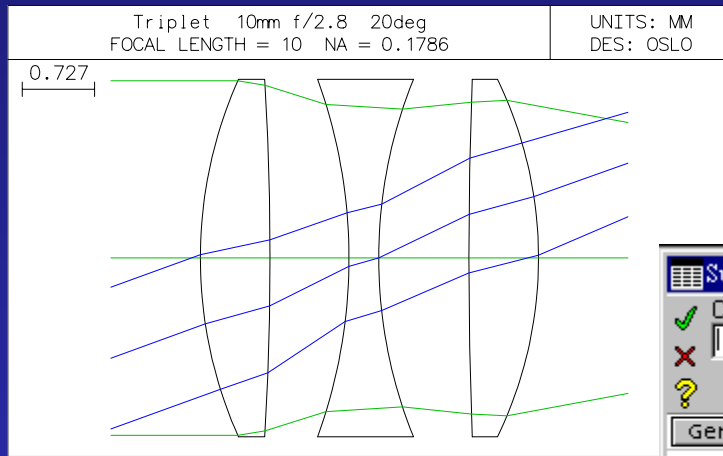


```
*ITERATE FULL 10
NBR      DAMPING      MIN ERROR      CON ERROR      PERCENT CHG.
0  1.0000e-08      3.821989      --
1  1.0000e-04      3.380152      --      11.560399
2  1.0000e-04      1.163296      --      65.584503
3  1.0000e-04      0.703656      --      39.511882
4  1.0000e-04      0.663520      --      5.703904
5  1.4380e-05      0.652843      --      1.609209
6  5.4530e-06      0.642279      --      1.618178
7  1.2734e-06      0.638169      --      0.639857
8  2.3317e-09      0.636724      --      0.226376
9  2.3317e-09      0.636276      --      0.070445
10 1.4359e-09      0.636060      --      0.033859

*ITERATE FULL 10
NBR      DAMPING      MIN ERROR      CON ERROR      PERCENT CHG.
0  1.0000e-08      0.636060      --
1  6.1580e-09      0.635971      --      0.014067
2  2.3352e-09      0.635934      --      0.005790
3  3.3580e-10      0.635919      --      0.002292
```

Optimization – curvature radius and thickness

- Step 4: Checking
 - Checking the feature and the surface data



Surface Data

Command:

Gen Setup Wavelength Field Points Variables Draw On Group Notes

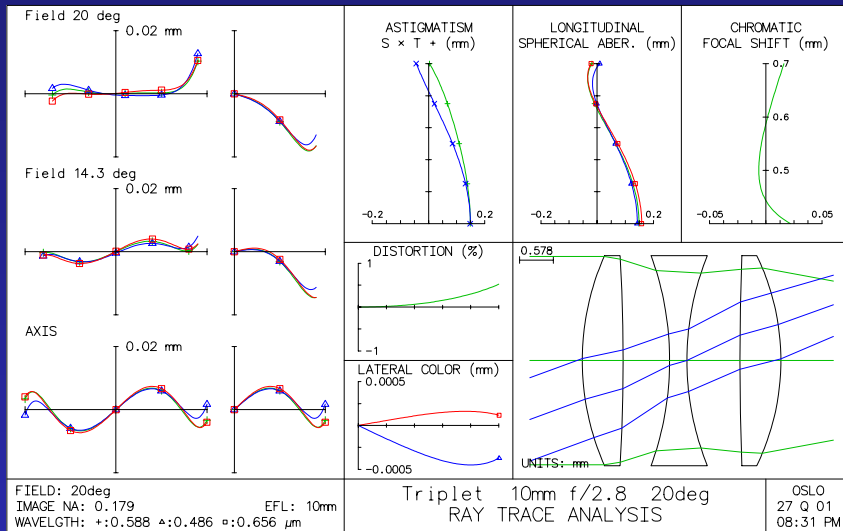
Lens: Triplet 10mm f/2.8 20deg Zoom 1 of 1 Efl 10.000028

Ent beam radius 1.785710 Field angle 20.000000 Primary wavln 0.587560

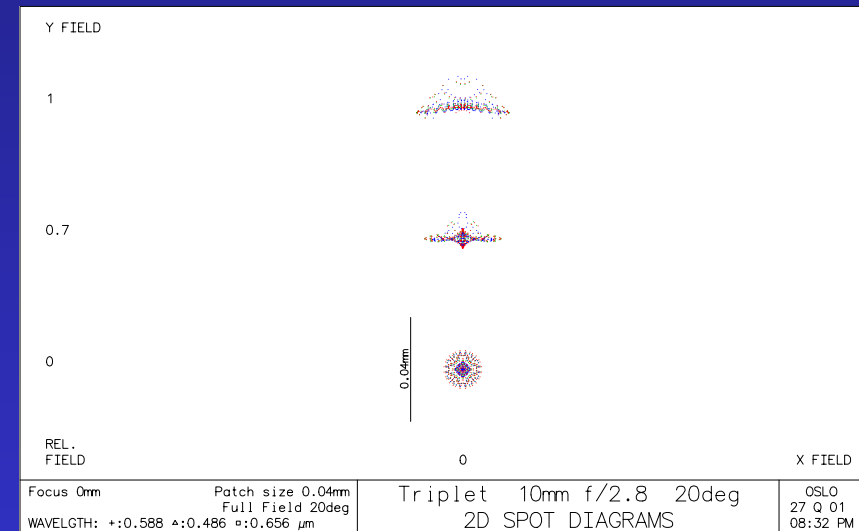
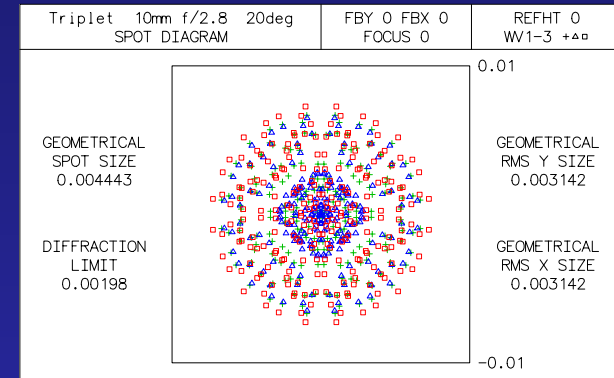
SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	2.0000e+19	7.2793e+18	AIR	
1	4.435328	0.700000	1.800000	SK16	C
2	-29.770091	0.793438	1.800000	AIR	
3	-5.296541	0.300000	1.800000	F4	C
AST	4.826185	0.905405	1.800000	AIR	
5	47.599148	0.700000	1.800000	SK16	C
6	-4.146896	8.316441	1.800000	AIR	
IMS	0.000000	0.000000	3.612958		

Optimization – curvature radius and thickness

- Checking the image quality
 - Ray analysis report graph



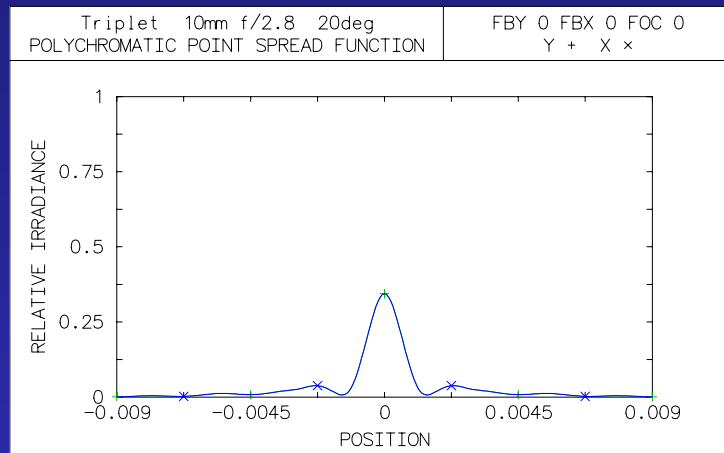
– Spot diagram report graph



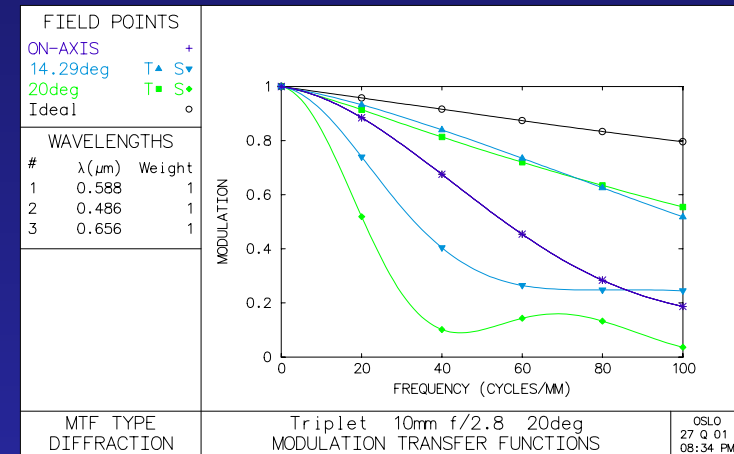
Optimization – curvature radius and thickness

- Step 4 : Checking the image quality

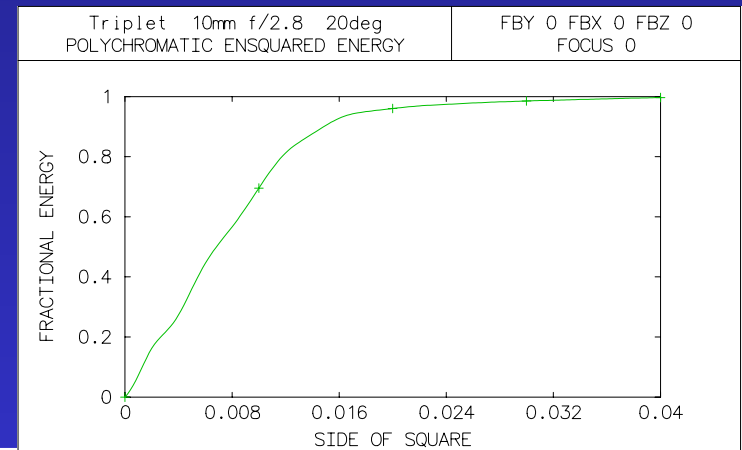
- PSF report graph



- MTF report graph



- Energy distribution report graph



Optimization – materials

- Setting variables & executing “iterate”
 - If the material of Srf 1 and Srf 5 could be changed and the materials of the two surfaces are the same.
 1. We define the “glass” of Srf 1 be “model” and Srf 5 “pickup” with Srf 1.
 2. Selecting the glass of Srf 1 to be variable (choosing “variable-RN/DN”).
 3. Defining the boundary of the two variables (1.5 to 1.8 on RN, 0 to 1 on DN)
 4. Executing “iterate” until it could not be improved.
 5. Fixing the glass into commercial glass.

Optimization – materials

- Setting variables & executing iterate
 - Step 1: set Srf 1 to be a model glass and define it as a variable.

Surface Data

pk gla 1

Gen Setup Wavelength Field Points Variables Draw On Group Notes

Lens: Triplet 10mm f/2.8 20deg Zoom 1 of 1 Efl 10.000028

Ent beam radius 1.785710 Field angle 20.000000 Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	2.0000e+19	7.2793e+18	AIR	
1	4.435144	0.700000	1.800000	GLASS1	M
2	-29.773449	0.793406	1.800000	AIR	
3	-5.297242	0.300000	1.800000	F4	C
AST	4.825782	0.905613	1.800000	AIR	
5	47.571406	0.700000	1.800000	GLASS1	P
6	-4.147320	8.316356	1.800000	AIR	
IMS	0.000000	0.000000	3.612960	S	

“M” means the glass of srf 1 was set as “model”

Field Points Variables Draw On Group Notes

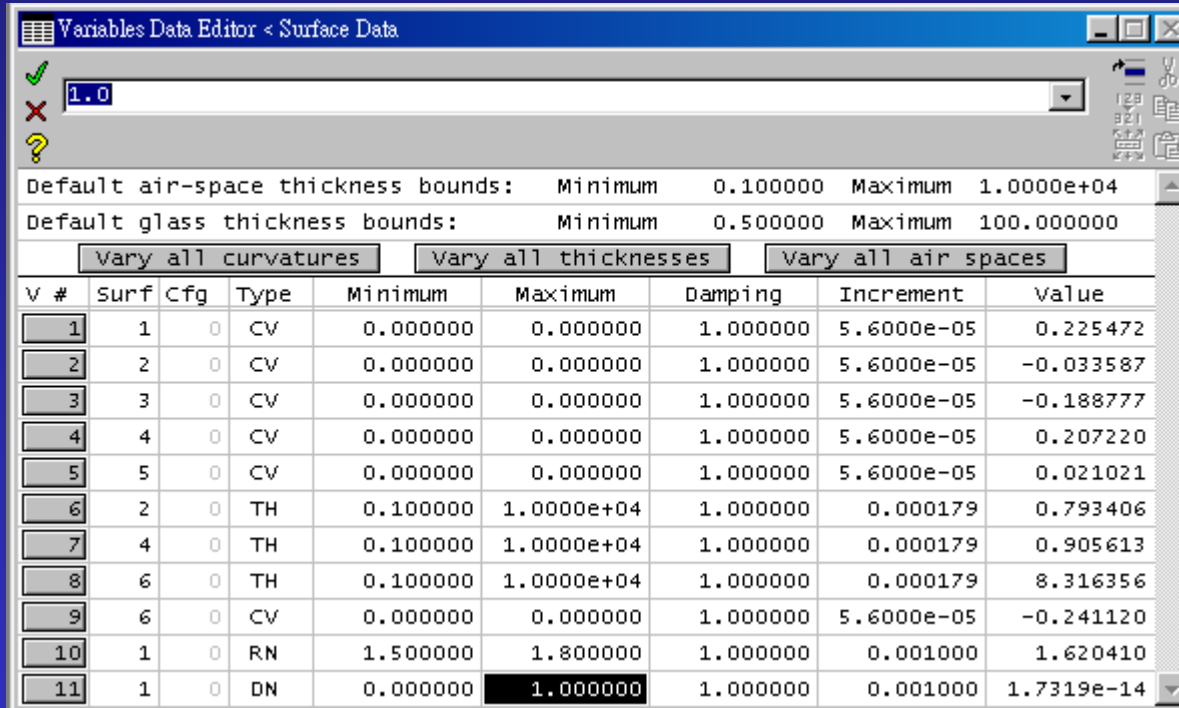
0deg Zoom 1 of 1 Efl 10.000028

Field angle 20.000000 Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	2.0000e+19	7.2793e+18	AIR	
1	4.435144	0.700000	1.800000	GLASS1	V
2	-29.773449	0.793406	1.800000	AIR	
3	-5.297242	0.300000	1.800000	F4	C
AST	4.825782	0.905613	1.800000	AIR	
5	47.571406	0.700000	1.800000	GLASS1	P
6	-4.147320	8.316356	1.800000	AIR	
IMS	0.000000	0.000000	3.612960	S	

Optimization – materials

- Setting variables & executing iterate
 - Step 2: define the boundary of variables.
 - Using “Optimize >> Variables ” to define the boundary of RN and DN.



Variables Data Editor < Surface Data

1.0

Default air-space thickness bounds: Minimum 0.100000 Maximum 1.0000e+04

Default glass thickness bounds: Minimum 0.500000 Maximum 100.000000

Vary all curvatures Vary all thicknesses Vary all air spaces

V #	Surf	Cfg	Type	Minimum	Maximum	Damping	Increment	Value
1	1	0	CV	0.000000	0.000000	1.000000	5.6000e-05	0.225472
2	2	0	CV	0.000000	0.000000	1.000000	5.6000e-05	-0.033587
3	3	0	CV	0.000000	0.000000	1.000000	5.6000e-05	-0.188777
4	4	0	CV	0.000000	0.000000	1.000000	5.6000e-05	0.207220
5	5	0	CV	0.000000	0.000000	1.000000	5.6000e-05	0.021021
6	2	0	TH	0.100000	1.0000e+04	1.000000	0.000179	0.793406
7	4	0	TH	0.100000	1.0000e+04	1.000000	0.000179	0.905613
8	6	0	TH	0.100000	1.0000e+04	1.000000	0.000179	8.316356
9	6	0	CV	0.000000	0.000000	1.000000	5.6000e-05	-0.241120
10	1	0	RN	1.500000	1.800000	1.000000	0.001000	1.620410
11	1	0	DN	0.000000	1.000000	1.000000	0.001000	1.7319e-14

Optimization – materials

- Setting variables & executing iterate
 - Step 3: execute iterates and fix the glass.

The screenshot shows the OSLO Premium Edition software interface. A context menu is open for the 'GLASS1' surface, with 'Fix' selected. A dialog box asks to change the glass to LAK33. The 'Surface Data' window shows the current lens design with LAK33 selected for surface 1.

OSLO Premium Edition

Change glass to LAK33 ?
Press Ok (or Return) to continue...

確定 取消

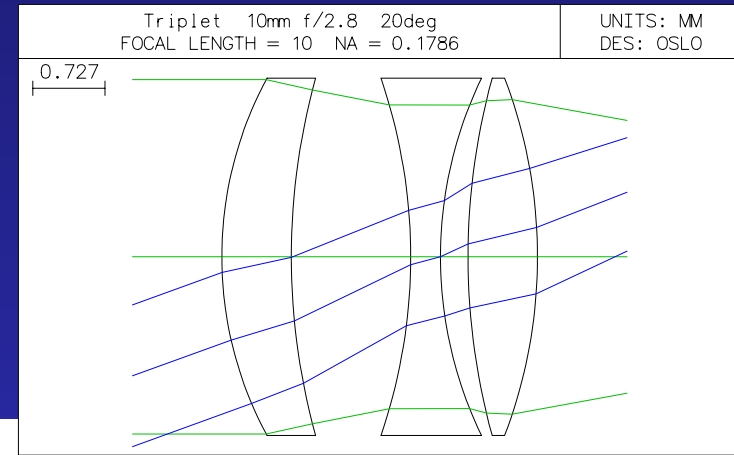
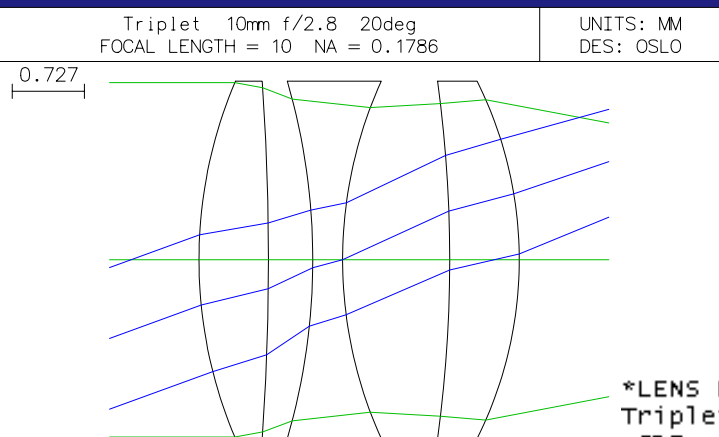
Surface Data

en	Setup	Wavelength	Field Points	Variables	Draw On	Group	Notes
ns: Triplet	10mm f/2.8	20deg	Zoom	1 of 1	Efl	10.711285	
t beam radius	1.785710	Field angle	20.000000	Primary wavln	0.587560		
RF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL		
BJ	0.000000	2.0000e+19	7.2793e+18	AIR			
1	4.542071	V	0.700000	K	LAK33	C	
2	-21.478629	V	0.417098	V	1.800000	P	
3	-6.157036	V	0.300000		1.800000		
AST	4.306178	V	1.031684	V	1.800000	A	
5	-12.588176	V	0.700000		1.800000		
6	-4.348732	V	8.329028	V	1.800000	K	
IMS	0.000000		0.000000		3.737925	S	

Optimization – materials

• Checking

- The TH[2] is too close to Srf. 3, and the image quality is not good.
- Enter 1.2 as TH[2] and re-optimize the system.

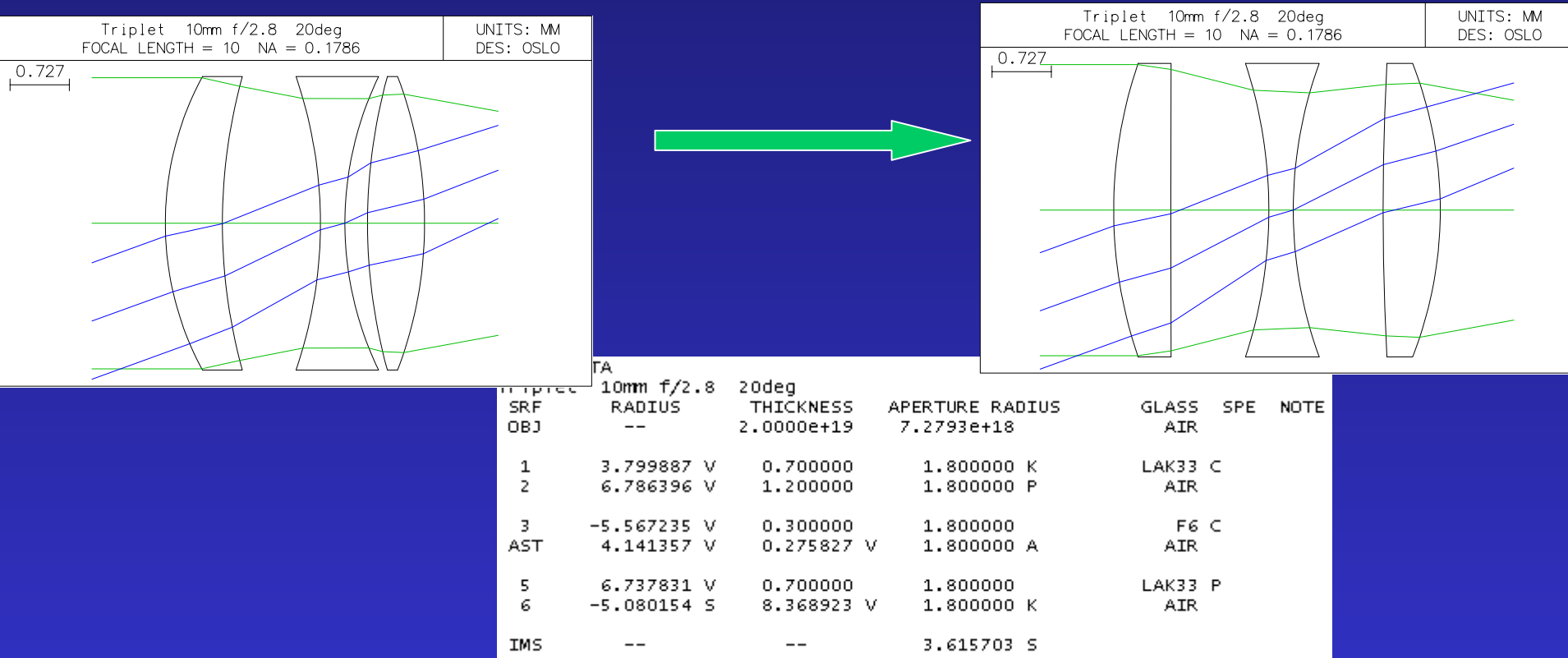


*LENS DATA

Triplet 10mm f/2.8 20deg							
SRF	RADIUS	THICKNESS	APERTURE	RADIUS	GLASS	SPE	NOTE
OBJ	--	2.0000e+19	7.2793e+18		AIR		
1	4.612761 V	0.700000	1.800000 K		LAK33	C	
2	-25.957550 V	0.444876 V	1.800000 P		AIR		
3	-6.470545 V	0.300000	1.800000		F6	C	
AST	4.348035 V	1.078110 V	1.800000 A		AIR		
5	-13.286459 V	0.700000	1.800000		LAK33	P	
6	-4.040565 S	8.293160 V	1.800000 K		AIR		
IMS	--	--	3.571527 S				

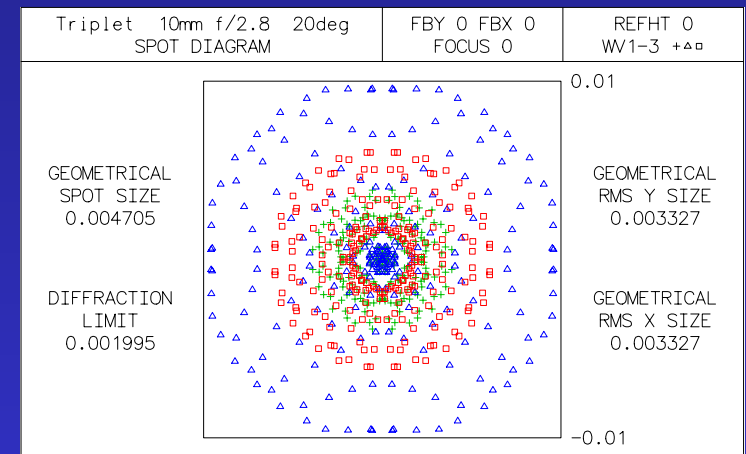
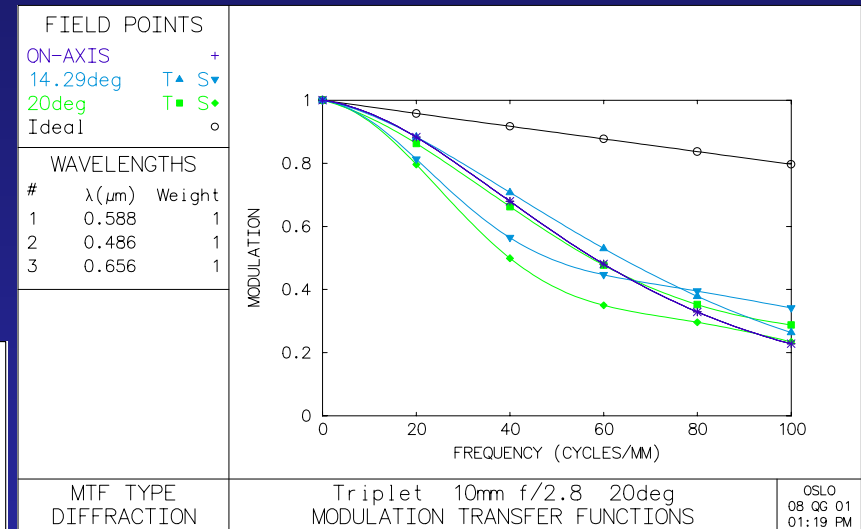
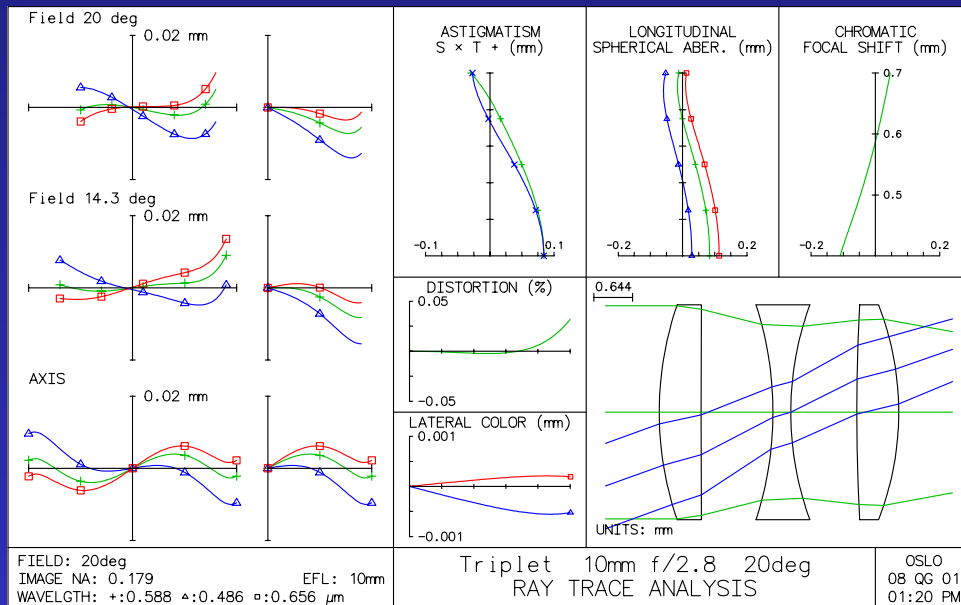
Optimization – materials

- Checking
 - TH[4] is too close to Srf 5
 - We setting TH[4] as 1.1 and re-optimize again.

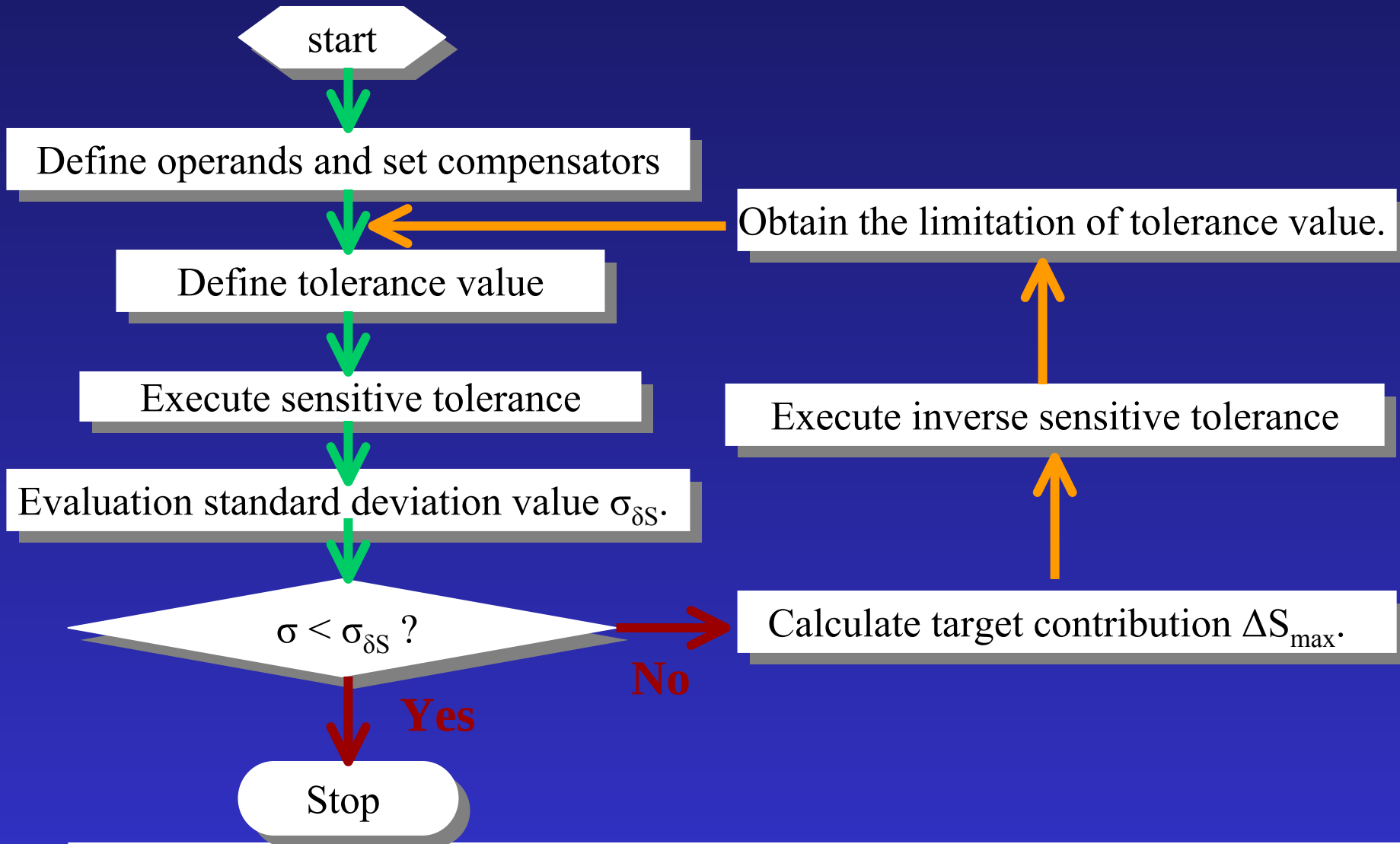


Optimization – the image quality after re-optimize

- Checking
 - Checking the image equality



Tolerance analysis



Tolerance analysis

- Sensitive tolerance

- The change in system performance S from nominal performance S_0

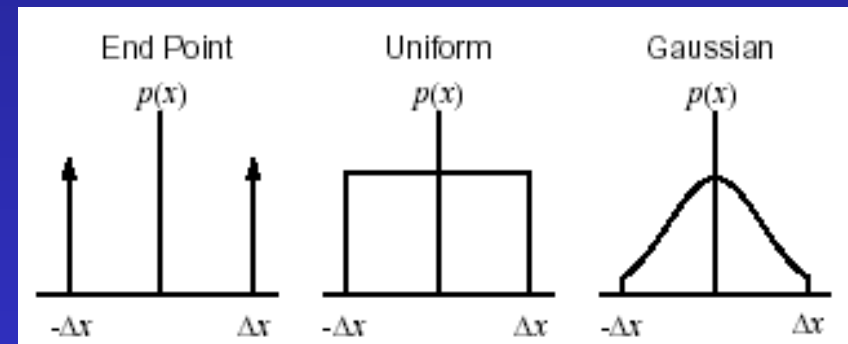
$$\delta S = S - S_0$$

- The value of standard deviation $\sigma_{\delta S}$ is dependent on the probability distribution parameter κ and performance change.

$$\sigma_{\delta S} = \kappa \sqrt{\sum_{i=1}^n (\Delta S_i)^2}$$

- κ is the probability distribution parameter, which depends on the distribution function.

Distribution	κ
End point	1.0
Uniform	0.58
Guassian	0.44



Tolerance analysis

- Inverse-sensitive tolerance

- The probability of success is dependent on the ratio of acceptable performance change $\delta S_{\max}$ to standard deviation $\sigma_{\delta S}$.

$\delta S_{\max} / \sigma_{\delta S}$	Probability of success
0.67	0.50
0.8	0.58
1.0	0.68
1.5	0.87
2.0	0.95
2.5	0.99

- The allowed performance change for each construction parameters :

$$\Delta S_{tar} = \frac{\sigma_{\delta S}}{\kappa \sqrt{n}}$$

- ΔS_{tar} : the target value of ΔS_i
- n : the number of construction parameters to be considered.

Tolerance – element thickness

- Step 1: Defining operands and setting compensator
 - Let TH[6] to be a variable which could be used as compensator. Click the “Var” in the text window to check the variable.
- We will use the RMS-spot size in three wavelength to calculate the tolerance.
 - Select “Optimize >> Generate Error Function >> OSLO Spot Size/Wavefront ” and accept the defaults.
 - Click “Ope” in the text window to check the operands.

```
*VARIABLES
VB  SN  CF  TYP      MIN      MAX      DAMPING      INCR      VALUE
V 1   6  -  TH      0.100000  1.0000e+04  1.000000      0.000179  8.269626
```

```
*OPERANDS
OP  MODE  WGT      NAME      VALUE  %CNTRB  DEFINITION
0 8    M    0.250000  Yrms1     0.001859  4.57  RMS
0 23   M    0.500000  Xrms2     0.003978  41.88 RMS
0 38   M    0.500000  Yrms2     0.002314  14.18 RMS
0 53   M    0.125000  Xrms3     0.003153   6.58 RMS
0 68   M    0.125000  Yrms3     0.007039  32.79 RMS
MIN RMS ERROR:      0.003549
```

Tolerance – element thickness

- Step 2: Defining the desired tolerance value
 - Use “lens >> show Tolerance Data >> Surface” to display the default tolerance (ISO10110) in the text window.

```

*SURFACE TOLERANCES
Triplet 10mm f/2.8 20deg

```

SRF	CON	CNST	CC TOL	RADIUS	RD TOL	PWR	IRR	TLC TOL	DZ TOL	THICKNESS	TH TOL	GLASS	V TOL	RN TOL	DECEN	TILT
															Y/X	A/B
1		5.6128	--			5.00	1.00	0.7000	0.1000			LAK33	0.0010		--	0.5000
		--	--					--	--				0.8000		--	0.5000
2		242.1348	--			5.00	1.00	1.2000	0.1000			AIR	--		--	0.5000
		--	--					--	--				--		--	0.5000
3		-5.9080	--			5.00	1.00	0.3000	0.1000			F4	0.0010		--	0.5000
		--	--					--	--				0.8000		--	0.5000
4		5.2616	--			5.00	1.00	1.1000	0.1000			AIR	--		--	0.5000
		--	--					--	--				--		--	0.5000
5		33.7801	--			5.00	1.00	0.7000	0.1000			LAK33	0.0010		--	0.5000
		--	--					--	--				0.8000		--	0.5000
6		-5.0874	--			5.00	1.00	8.2696	0.1000			AIR	--		--	0.5000
		--	--					--	--				--		--	0.5000
7		--	--			--	--	--	--						--	--
		--	--					--	--						--	--

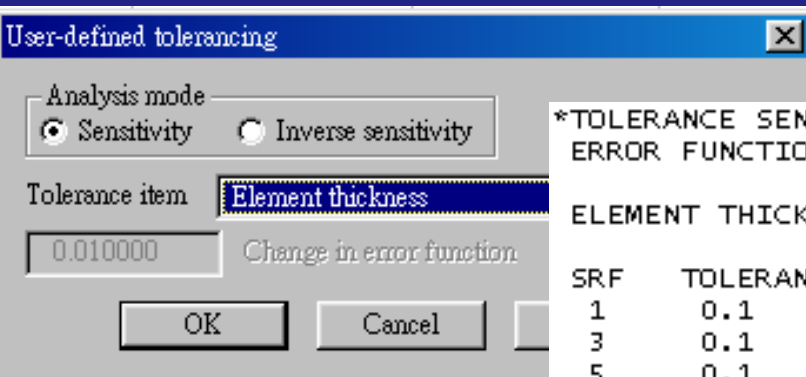
```

FRINGE WAVELENGTH: 0.546070
Fringes measured over clear aperture of surface unless indicated.
Tilt tolerances are specified in degrees.

```

Tolerance – element thickness

- Step 3 : Executing sensitive tolerance
 - Use “Tolerance >> User-Defined Tolerancing”, choose the “sensitive” mode and select the tolerance item you desired.
 - We will do the “element thickness ” tolerance first.



*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM: 0.003549

ELEMENT THICKNESS TOLERANCE

SRF	TOLERANCE	PLUS PERT	MINUS PERT	PLUS PERT	MINUS PERT
1	0.1	0.007235	0.005902	9.9895e-05	8.2635e-06
3	0.1	0.002551	0.001333	0.002291	0.000201
5	0.1	0.000873	0.000236	0.000873	-5.4004e-05

STATISTICAL SUMMARY

	UNCOMPENSATED	COMPENSATED
WORST CASE CHANGE	0.010659	0.003264
STANDARD DEVIATION		
RSS	0.007721	0.002454
UNIFORM	0.004458	0.001417
GAUSSIAN	0.003396	0.001079

COMPENSATOR STATISTICS

COMP	MEAN	STD DEV	MAX	RSS
TH	6	-0.001367	0.062540	0.104528
				0.108525

Nominal value

Tolerance – element thickness

- Step 4 : Evaluation
 - Let the maximum allowed spot size is $18\text{ }\mu\text{m}$. Since the nominal value of spot size is $3.55\text{ }\mu\text{m}$, the maximum allowed change is $14.45\text{ }\mu\text{m}$ (δS_{max}).
 - If we desire the probability success rate to be 99%, then the desired standard deviation is $5.78\text{ }\mu\text{m}$ (0.00578 mm).
 - Since the standard deviation of uncompensated is 0.004458 , smaller than the desired value, the default element thickness tolerance value (0.1 mm) is acceptable.

Tolerance – surface tilt

- Step 1: Use the default operands (ISO10110).
- Step 2: Execute sensitive tolerance again.
 - Select “Surface tilt-TLA” in User-Define Tolerance dialog box and the result will be displayed in the text window.

```
*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:      0.003549

SURFACE TILT TOLERANCE (TLA)
ERROR FUNCTION CHANGE
SRF  TOLERANCE  PLUS PERT  MINUS PERT  PLUS PERT  MINUS PERT
1    0.5        0.017180  0.016576  0.014877  0.012827
2    0.5        0.015939  0.015982  0.014685  0.015471
3    0.5        0.013344  0.013304  0.013344  0.013217
4    0.5        0.010454  0.011652  0.007860  0.010137
5    0.5        0.014167  0.013432  0.013704  0.012222
6    0.5        0.016655  0.016955  0.016267  0.016944

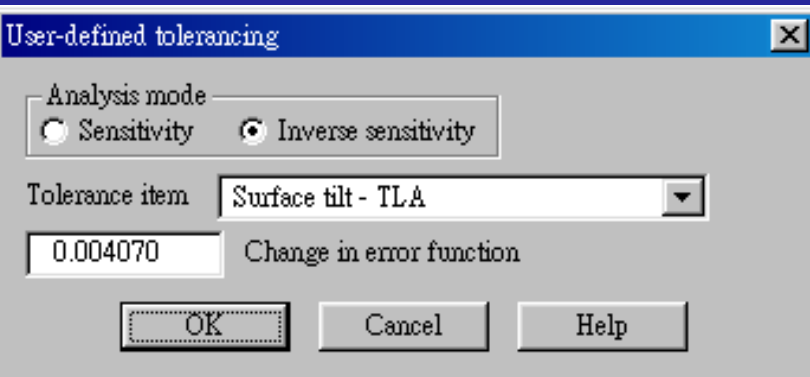
STATISTICAL SUMMARY
UNCOMPENSATED  COMPENSATED
WORST CASE CHANGE  0.089281  0.084477
STANDARD DEVIATION
  RSS  0.036778  0.034877
  UNIFORM  0.021234  0.020136
  GAUSSIAN  0.016175  0.015339

COMPENSATOR STATISTICS
COMP  MEAN  STD DEV  MAX  RSS
TH    6   -0.004503  0.068905  0.120119  0.169713
```

Tolerance – surface tilt

- Step 3 : Evaluation

- The calculation is the same as the tolerance calculation of element thickness. The desired standard deviation is 0.00578 mm.
- The target performance change Δs_{tar} is 0.00407.
- Select “Inverse sensitive” and “Surface tilt-TLA” in User-define Tolerance dialog box, and enter 0.00407 in the “change in Error Function” field.



```
*INVERSE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:      0.003549
ALLOWED CHANGE IN ERROR FUNCTION:      0.004070

SURFACE TILT TOLERANCE (TLA)
          ALLOWED TOLERANCE
SRF      UNCOMPENSATED      COMPENSATED
1         0.241096          0.253155
2         0.252149          0.253341
3         0.275963          0.275597
4         0.290162          0.306125
5         0.264962          0.266243
6         0.243841          0.242496
```

Tolerance – surface tilt

- Step 4: Update the tolerance value
 - Select “Tolerance >> Update tolerance Data >> Surface” to change values.
 - Without compensation, we set “TA TOL” about 0.2 for Surface 1 and 6, and 0.25 for surface 2, 3, 4 and 5.

Surface Tolerances Data Editor < Surface Data

0.2

Direct specification

SRF	RADIUS	RD TOL	PWR FR	IRR FR	THICK	TH TOL	GLASS	RN TOL	DY TOL	TA TOL
1	5.613	0.0	5.00	1.00	0.700	0.1000	LAK33	0.0010	0.0	0.2000
2	242.135	0.0	5.00	1.00	1.200	0.1000	AIR	0.0	0.0	0.2500
3	-5.908	0.0	5.00	1.00	0.300	0.1000	F4	0.0010	0.0	0.2500
4	5.262	0.0	5.00	1.00	1.100	0.1000	AIR	0.0	0.0	0.2500
5	33.780	0.0	5.00	1.00	0.700	0.1000	LAK33	0.0	0.0	0.2500
6	-5.087	0.0	5.00	1.00	8.270	0.0	AIR	0.0	0.0	0.2000
7	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0

FRINGE WAVELENGTH: 0.546070

Fringes measured over clear aperture of surface unless indicated.
Tilt tolerances are specified in degrees.

Display all surface tolerances: ☐ Yes ☒ No

Tolerance – surface tilt

- Step 5: Re-execute sensitive tolerance.
 - After re-executing, check the standard deviation.

```
*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:      0.003549

SURFACE TILT TOLERANCE (TLA)
ERROR FUNCTION CHANGE
SRF  TOLERANCE  PLUS PERT  MINUS PERT  PLUS PERT  MINUS PERT
1    0.2       0.005553  0.004928   0.004891   0.003318
2    0.25      0.006631  0.006724   0.005965   0.006548
3    0.25      0.005454  0.005405   0.005454   0.005348
4    0.25      0.003864  0.004859   0.002445   0.004345
5    0.25      0.006017  0.005279   0.005874   0.004620
6    0.2       0.005053  0.005377   0.004884   0.005377

STATISTICAL SUMMARY
UNCOMPENSATED  COMPENSATED
WORST CASE CHANGE  0.033984  0.032489
STANDARD DEVIATION
  RSS  0.008052  0.007721
  UNIFORM  0.008052  0.007721
  GAUSSIAN  0.008052  0.007721

COMPENSATOR STATISTICS
COMP  MEAN  STD DEV  MAX  RSS
TH    6   -0.001970  0.030981  0.047358  0.076236
```

Tolerance – surface tilt

- Step 6 : Re-set the tolerance value and re-execute sensitive tolerance.
 - Update the tilt tolerance about 0.2 for surface 2, 3 and 5.

```
*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:    0.003549

SURFACE TILT TOLERANCE (TLA)
      ERROR FUNCTION CHANGE      COMPENSATED CHANGE
SRF  TOLERANCE  PLUS PERT  MINUS PERT  PLUS PERT  MINUS PERT
1    0.2        0.005553   0.004928   0.004891   0.003318
2    0.2        0.004856   0.004952   0.004307   0.004850
3    0.2        0.003967   0.003919   0.003967   0.003868
4    0.25       0.003864   0.004859   0.002445   0.004345
5    0.2        0.004465   0.003750   0.004389   0.003204
6    0.2        0.005053   0.005377   0.004884   0.005377

STATISTICAL SUMMARY
      UNCOMPENSATED  COMPENSATED
WORST CASE CHANGE      0.029174    0.027819
STANDARD DEVIATION
  RSS      0.011882    0.011413
  UNIFORM  0.006918    0.006589
  GAUSSIAN  0.005278    0.005819

COMPENSATOR STATISTICS
COMP      MEAN      STD DEV      MAX      RSS
TH        6      -0.001729  0.029159  0.047358  0.071736
```

Tolerance – surface tilt

- Step 7 : Re-set the tolerance value and re-execute sensitive tolerance.
 - Update the tilt tolerance about 0.15 for surface 1, 2 and 6, and 0.2 for surface 3.

```
*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:      0.003549

SURFACE TILT TOLERANCE (TLA)

SRF  TOLERANCE  ERROR FUNCTION CHANGE      COMPENSATED CHANGE
      PLUS PERT  MINUS PERT      PLUS PERT  MINUS PERT
1     0.15      0.003743    0.003150    0.003357    0.001921
2     0.15      0.003164    0.003259    0.002735    0.003228
3     0.2       0.003967    0.003919    0.003967    0.003868
4     0.2       0.002658    0.003590    0.001503    0.003264
5     0.2       0.004465    0.003750    0.004389    0.003204
6     0.15      0.003275    0.003584    0.003139    0.003584

STATISTICAL SUMMARY
WORST CASE CHANGE      UNCOMPENSATED    COMPENSATED
STANDARD DEVIATION      0.022608        0.021790
  RSS      0.005273    0.005577
  UNIFORM  0.005355    0.005170
  GAUSSIAN  0.004079    0.003939

COMPENSATOR STATISTICS
COMP      MEAN      STD DEV      MAX      RSS
TH        6      -0.001358    0.023211    0.035430    0.056991
```

Smaller than the value
of desired standard
deviation(0.005577).

Tolerance – surface decenter(Y)

- The process are the same as surface tilting tolerance analysis.
 - Step 1: Set tolerance value 0.05 for all six surfaces and do sensitive tolerance.
 - Step 2: Set 0.00407 for inverse sensitive tolerance analysis to check the maximum allowed change value.
 - Step 3: Set tolerance value 0.2 for surface 1,3 and 4, 0.5 for surface 2 and 5, and 0.15 for surface 6. Re-run the tolerance analysis.

```

*TOLERANCE SENSITIVITY ANALYSIS
ERROR FUNCTION FOR NOMINAL SYSTEM:      0.003549

SURFACE DECENTRATION TOLERANCE (DCY)

      ERROR FUNCTION CHANGE          COMPENSATED CHANGE
SRF  TOLERANCE  PLUS PERT  MINUS PERT  PLUS PERT  MINUS PERT
1    0.02      0.005708    0.005079    0.005022    0.003440
2    0.05      2.1380e-05  3.6315e-05  -8.0858e-06  3.6315e-05
3    0.02      0.003744    0.003791    0.003696    0.003791
4    0.02      0.003117    0.003985    0.001827    0.003642
5    0.05      0.001272    0.000758    0.001272    0.000510
6    0.015     0.004251    0.003935    0.004251    0.003786

STATISTICAL SUMMARY

      UNCOMPENSATED  COMPENSATED
WORST CASE CHANGE      0.019045    0.018015
STANDARD DEVIATION
  RSS      0.009085    0.008518
  UNIFORM   0.005245    0.004918
  GAUSSIAN   0.003996    0.003746

COMPENSATOR STATISTICS
COMP      MEAN      STD DEV      MAX      RSS
TH        6      -0.002425    0.024503    0.048317    0.060825
  
```