TD OSLO

associé au cours d'optique géométrique avancée (4A-INSA)

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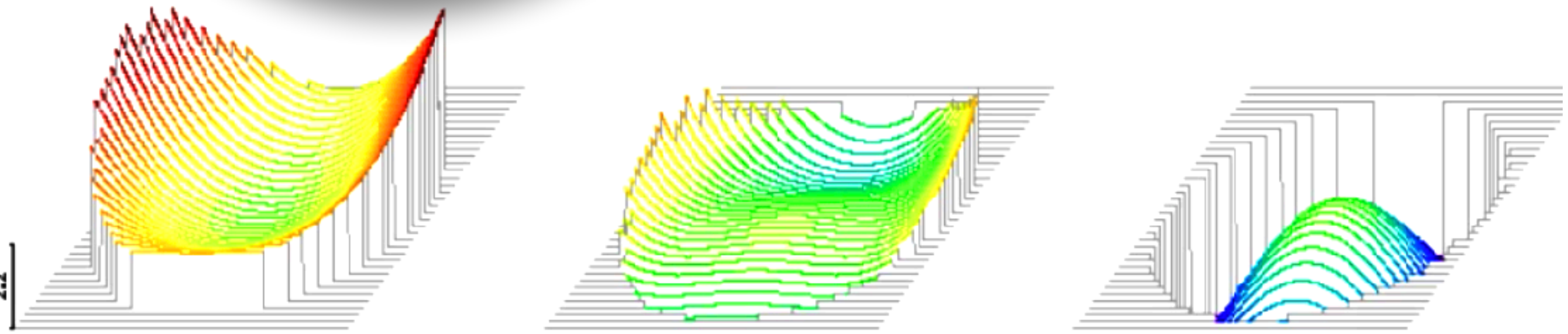

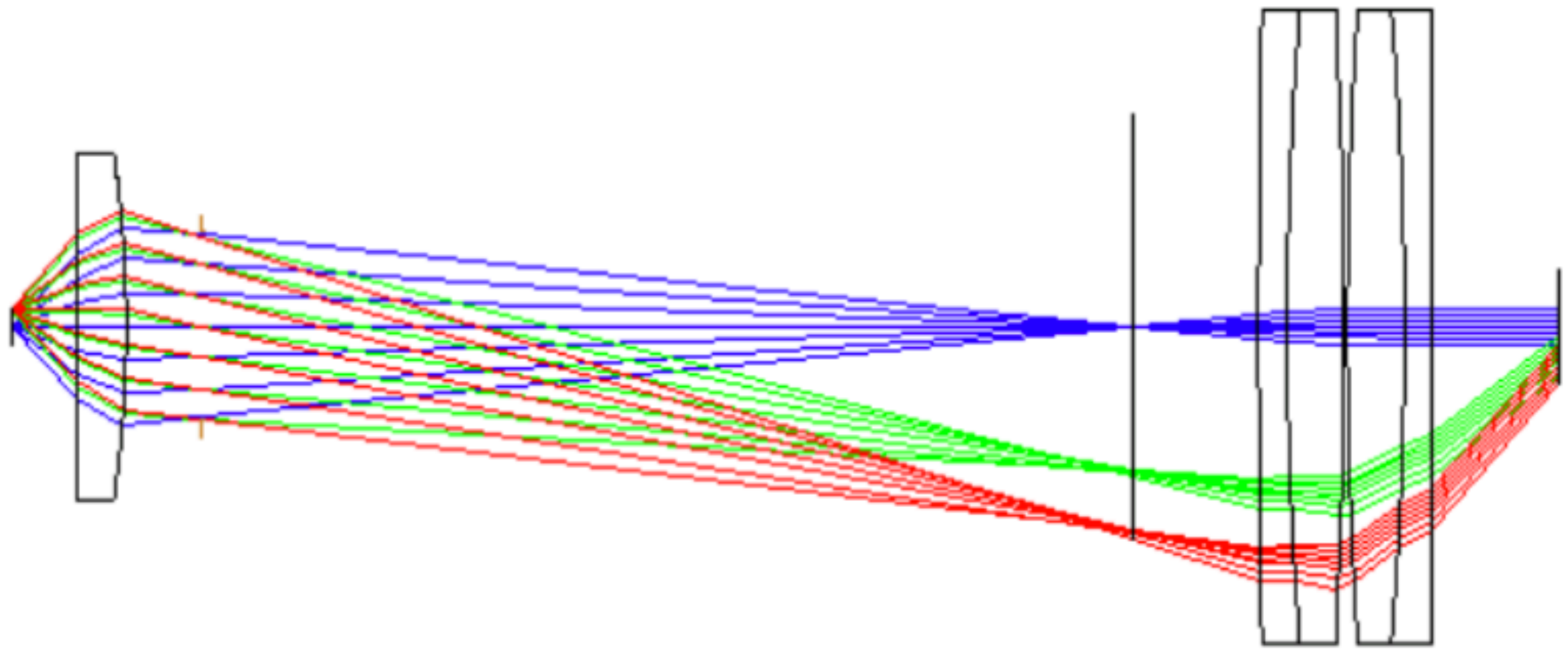

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Inspiré d'exercices extraits du site d'OSLO : https://lambdares.com/oslo-videos/

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.

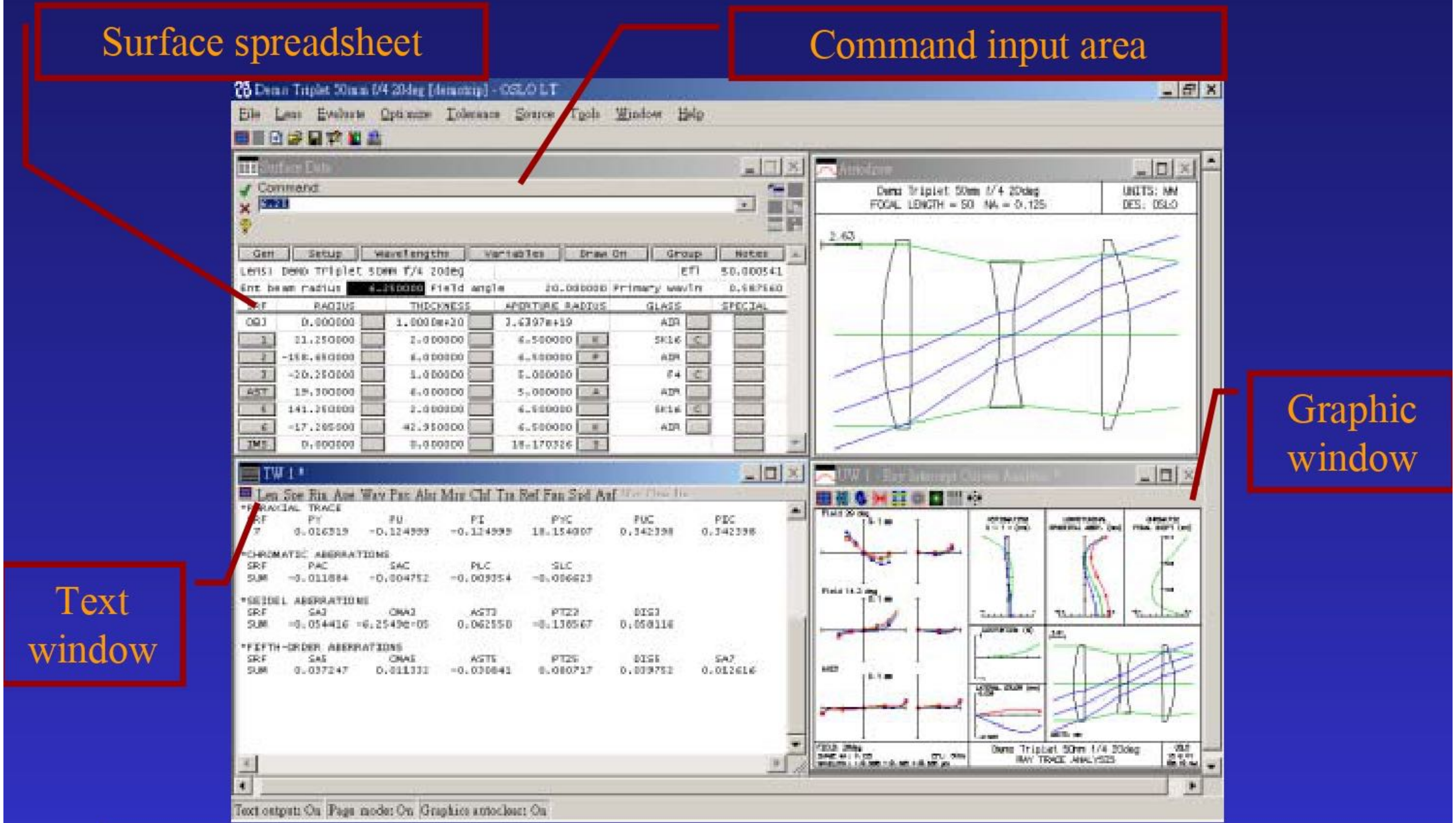
- The method of ray tracing used in OSLO is sequential ray tracing, but it also can execute non-sequential ray tracing.

- It can execute the optimization and tolerance analysis.

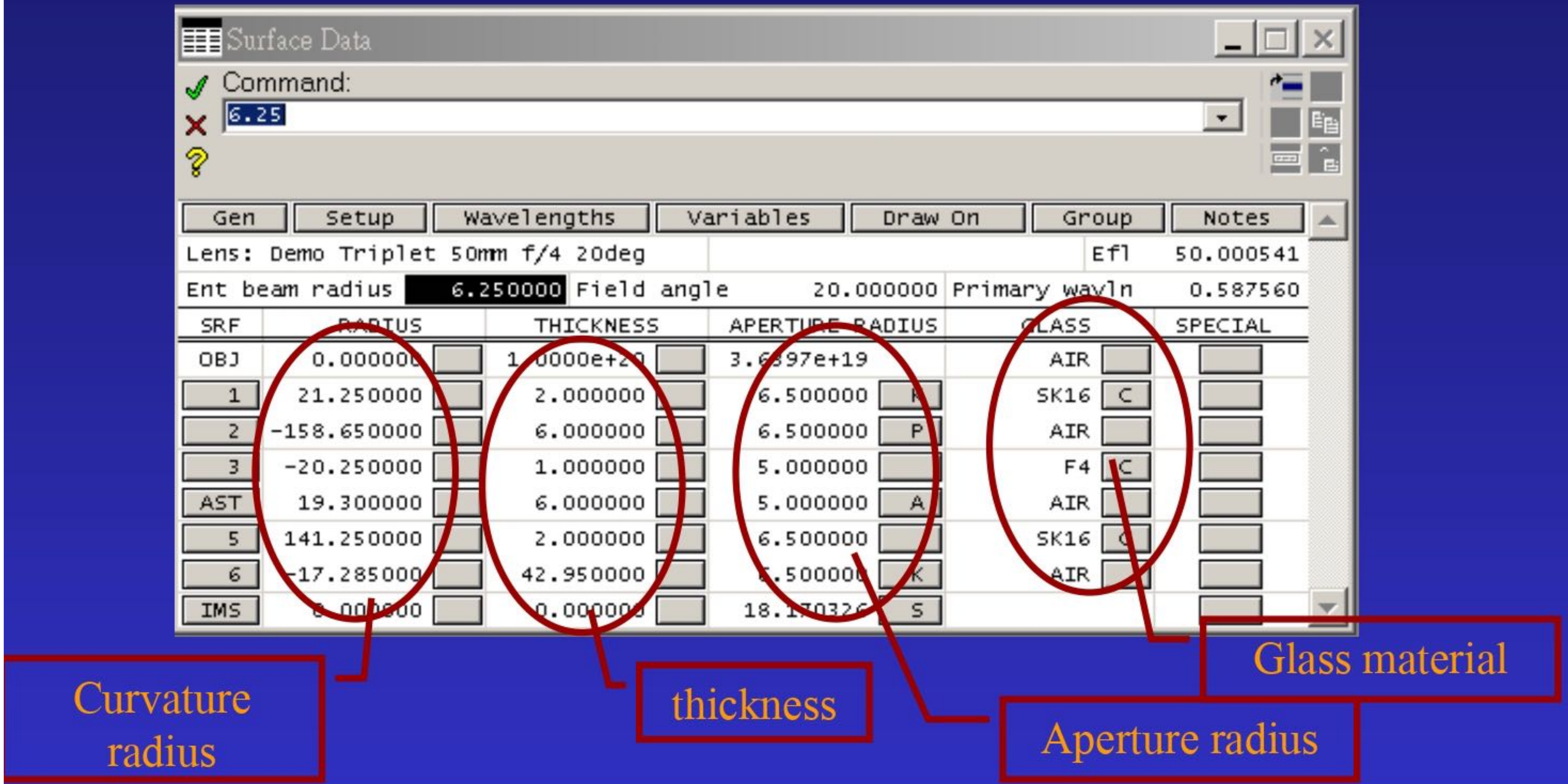
The advantage of OSLO

- 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 data spreadsheet



Text output

*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

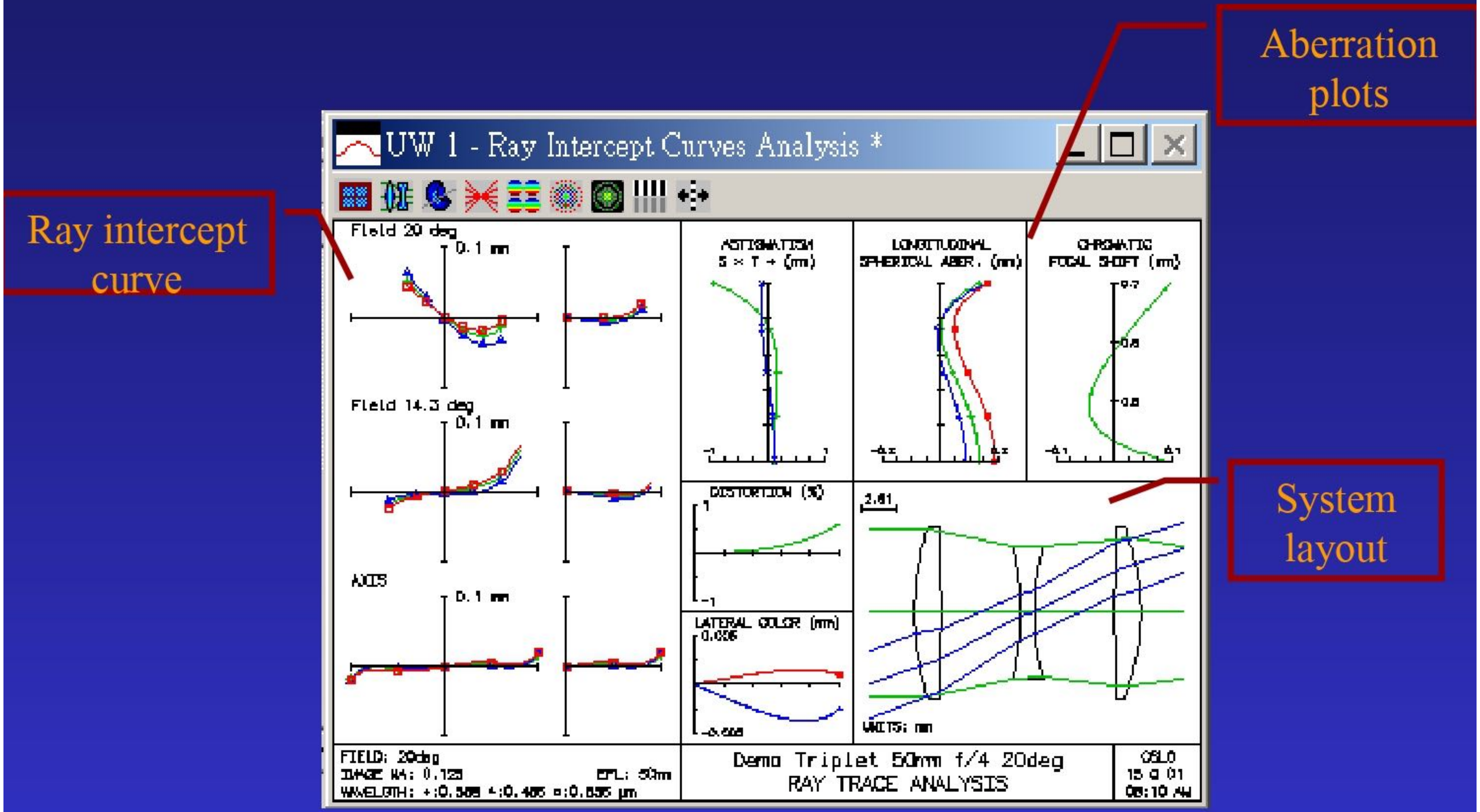
*SEIDEL ABERRATIONS

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



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

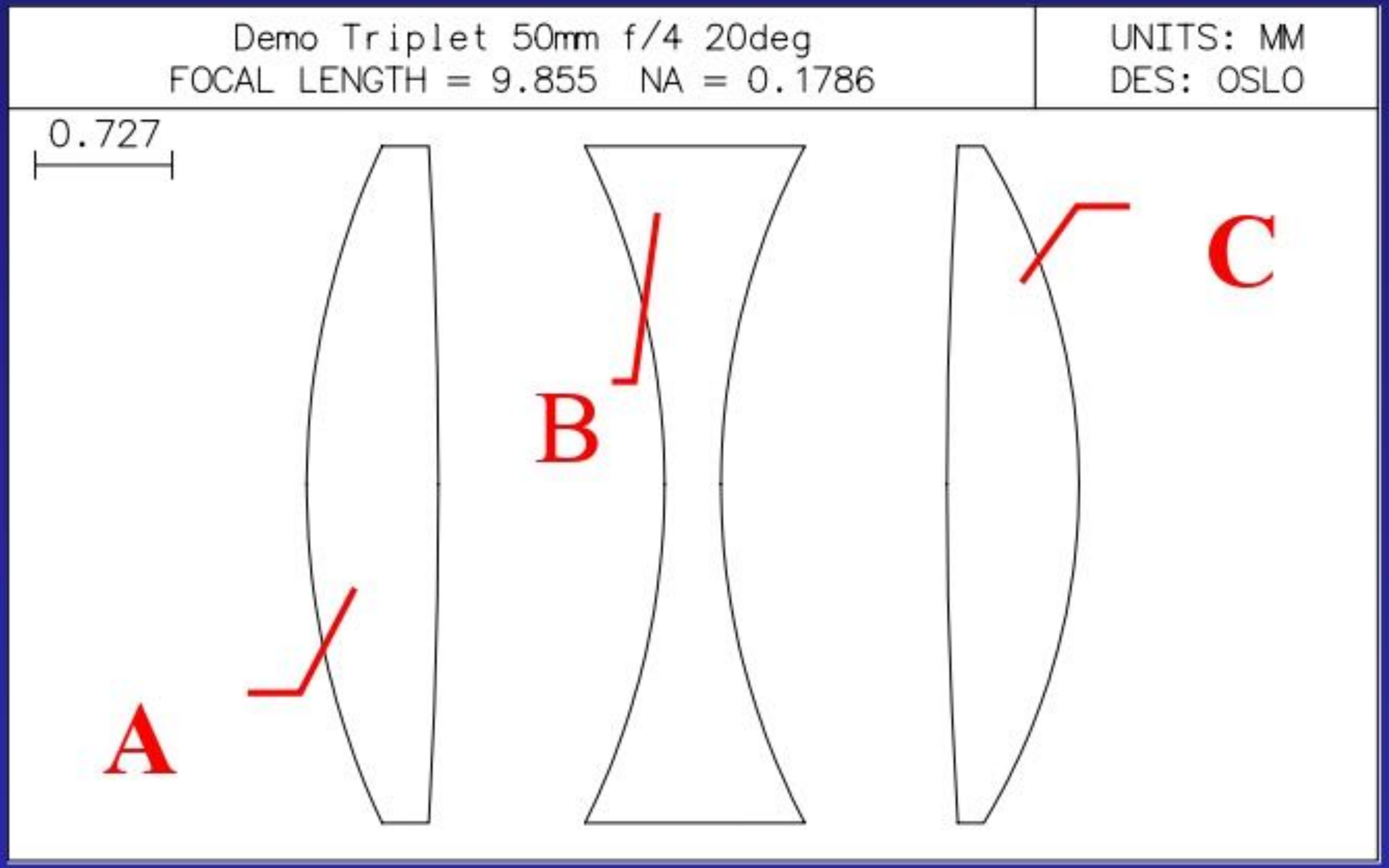
- It could not simulate physical optics.
- It could not do stray-light analysis of a system.
- It could not simulate complex light sources.

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 : 20º
- Aperture radius : 1.8mm
- materials:
  - Lens A and Lens C : SK16
  - Lens B : F4
- Working wavelengths
  - main : 0.5876 μm
  - 0. 4861 μm
  - 0. 6563 μm



The procedure of optical system design

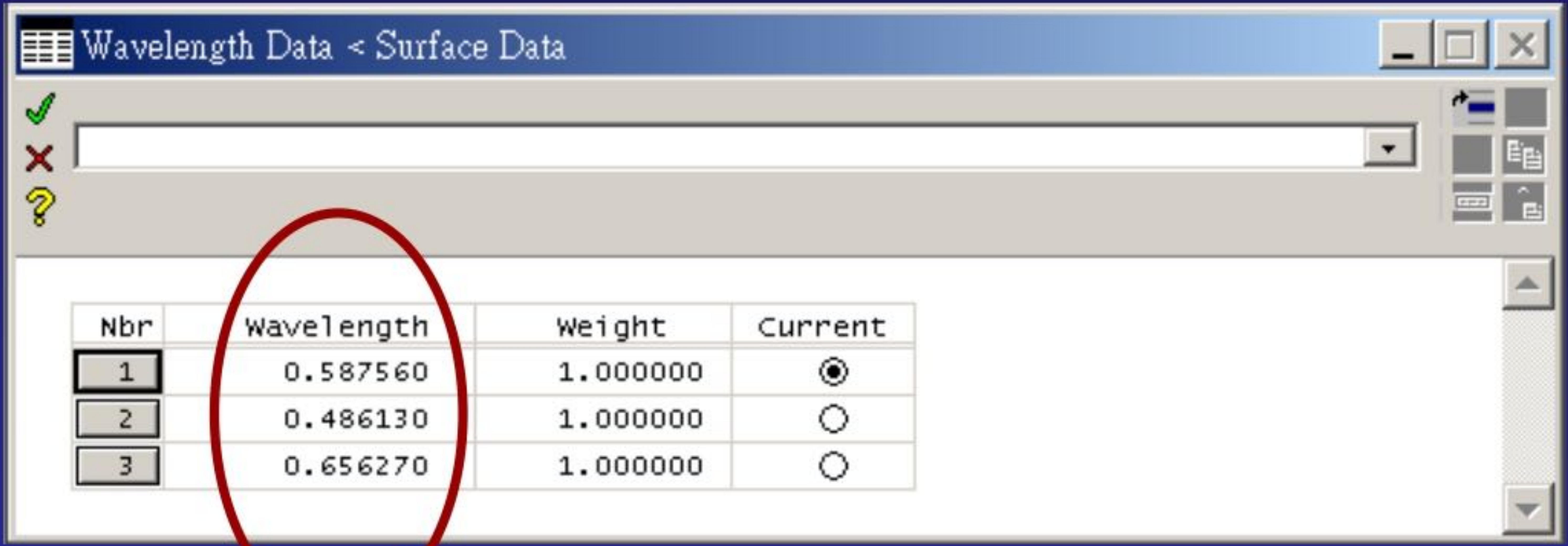
1. System data entry
2. Ray tracing
3. Checking optical performance
4. Optimization
5. Tolerance

Data entry

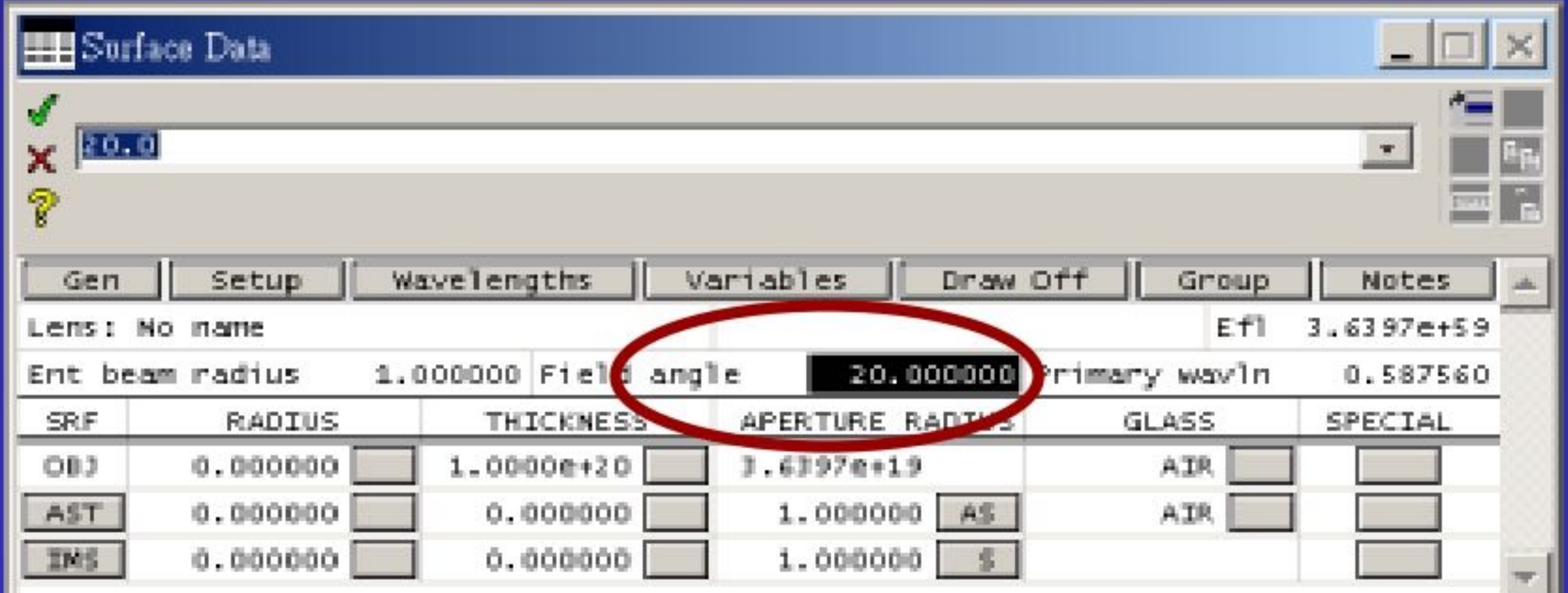
- System parameters
  - Wavelengths
  - Lens parameters
    - Curvature radius
    - Thickness
    - Aperture radius
    - Glass materials
  - Field angle
  - Paraxial parameters
    - Beam radius
    - f/#

Data entry – wavelength and field angle

- Wavelength

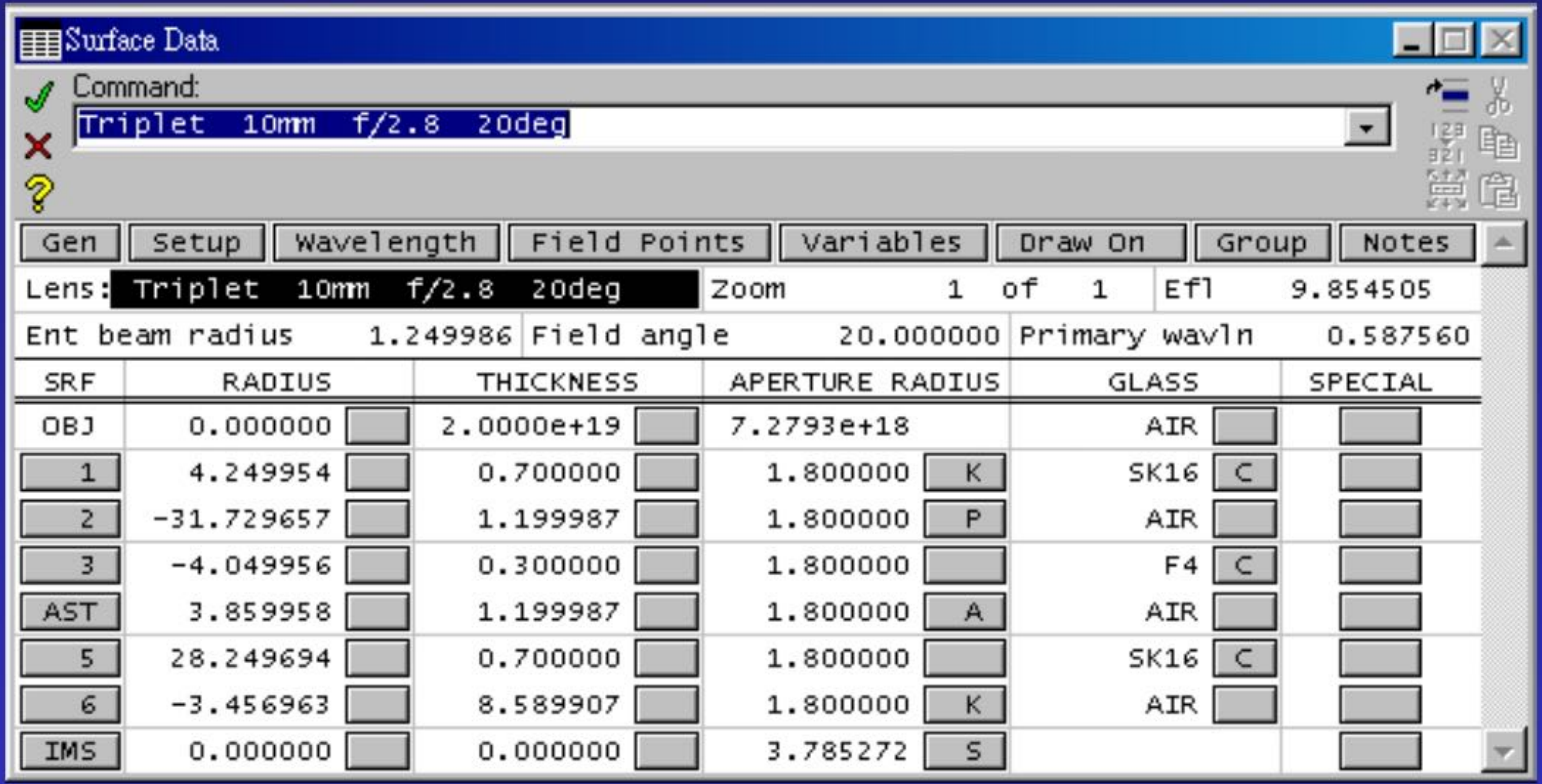


- Field angle



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.



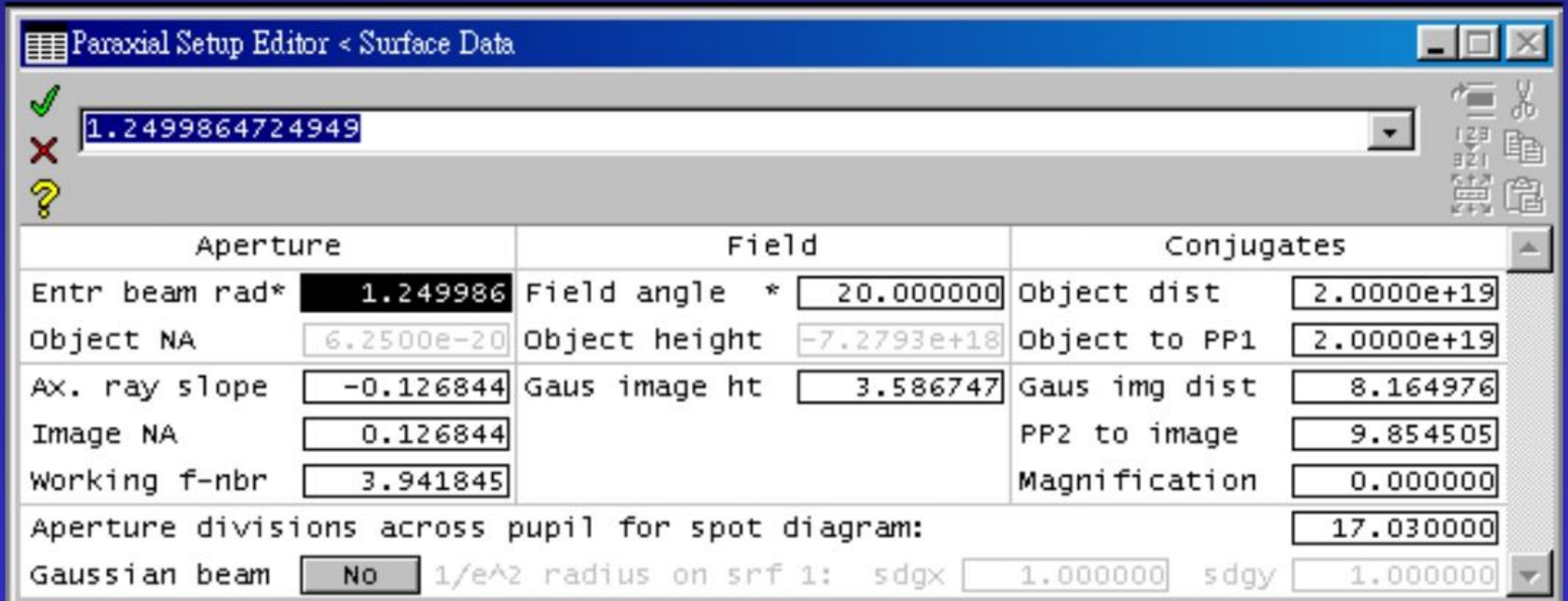
Data entry – paraxial parameters

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

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

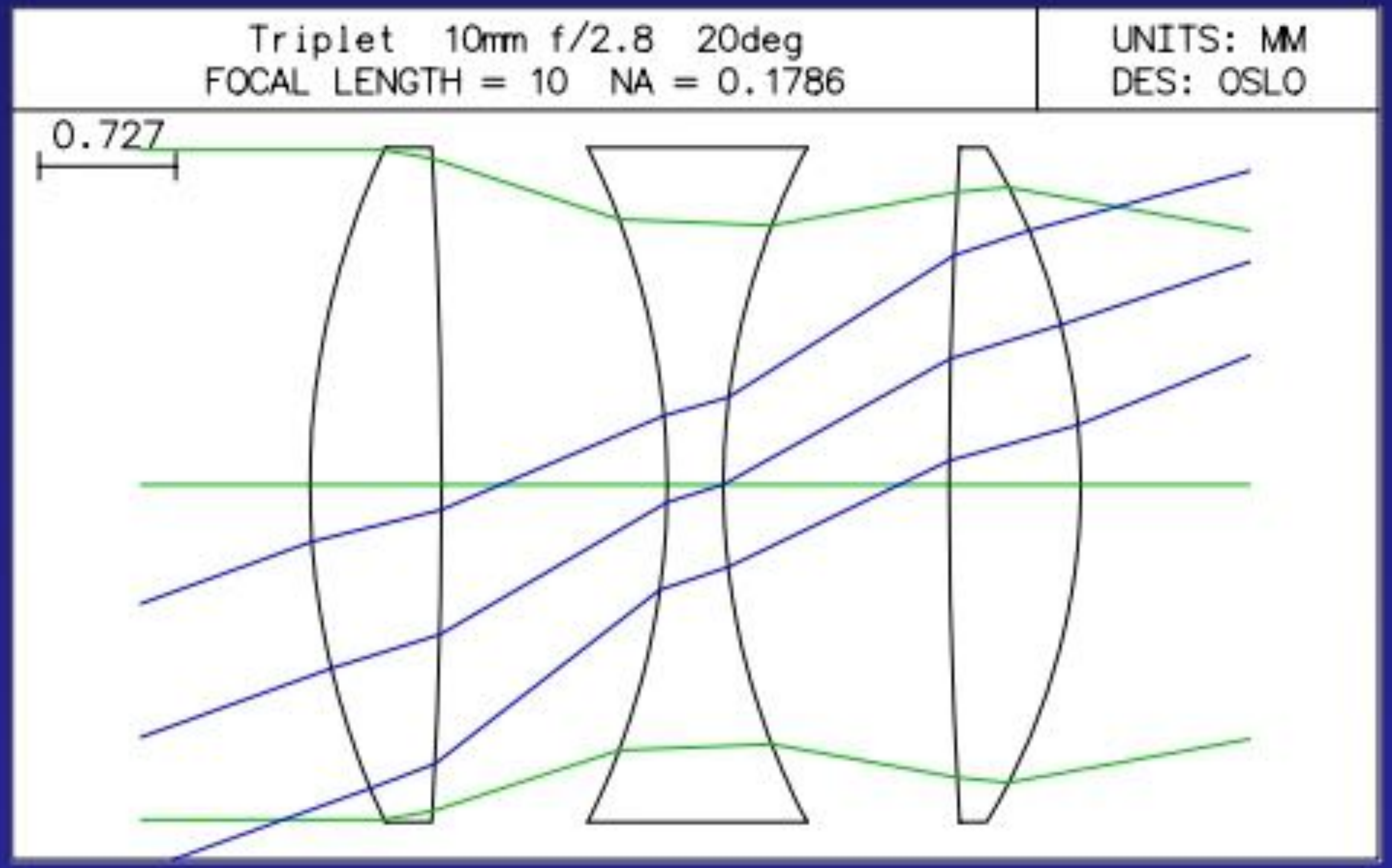
D=entrance beam radius

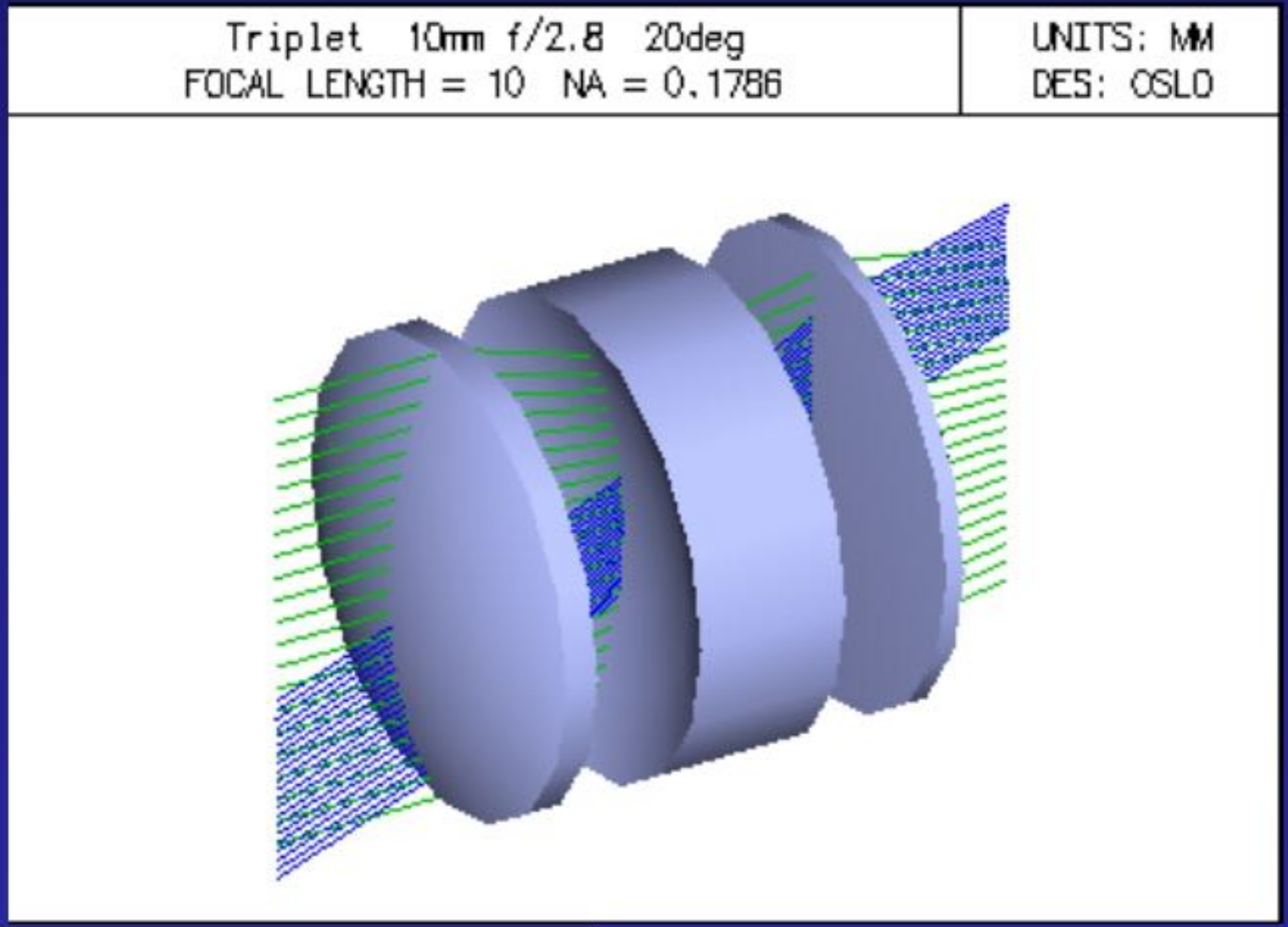
f=focal length



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

$$y' = y + tu$$

$$i = u + yc$$

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

*PARAXIAL TRACE

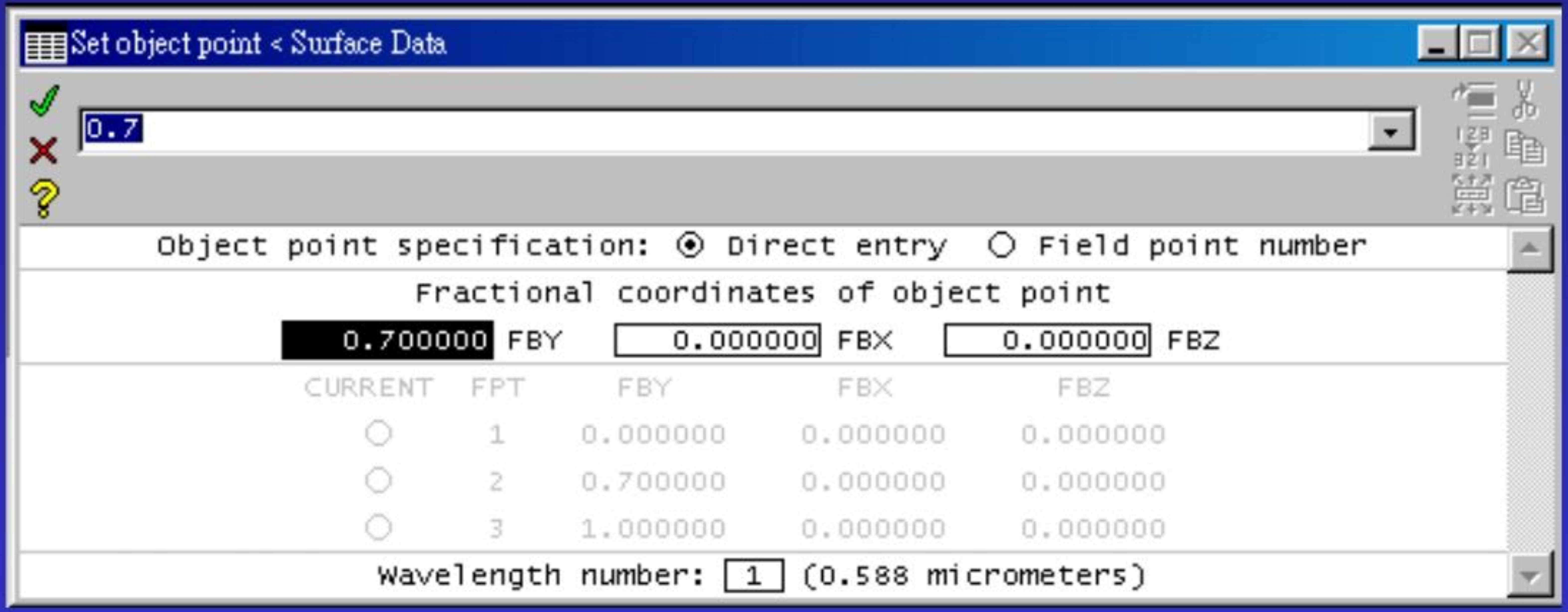
SRF	PY	PU	PI	PYC	PUC	PIC
0	--	8.9286e-20	8.9286e-20	-7.2793e+18	0.363970	0.363970
1	1.785710	-0.160872	0.420172	-0.922982	0.307766	0.146796
2	1.673100	-0.293393	-0.213602	-0.707546	0.512542	0.330065
3	1.321032	-0.057077	-0.619577	-0.092502	0.308339	0.535382
4	1.303909	0.116017	0.280727	-1.1102e-16	0.498459	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 (PY, PU, PI)

Chief rays (PYC, PUC, PIC)

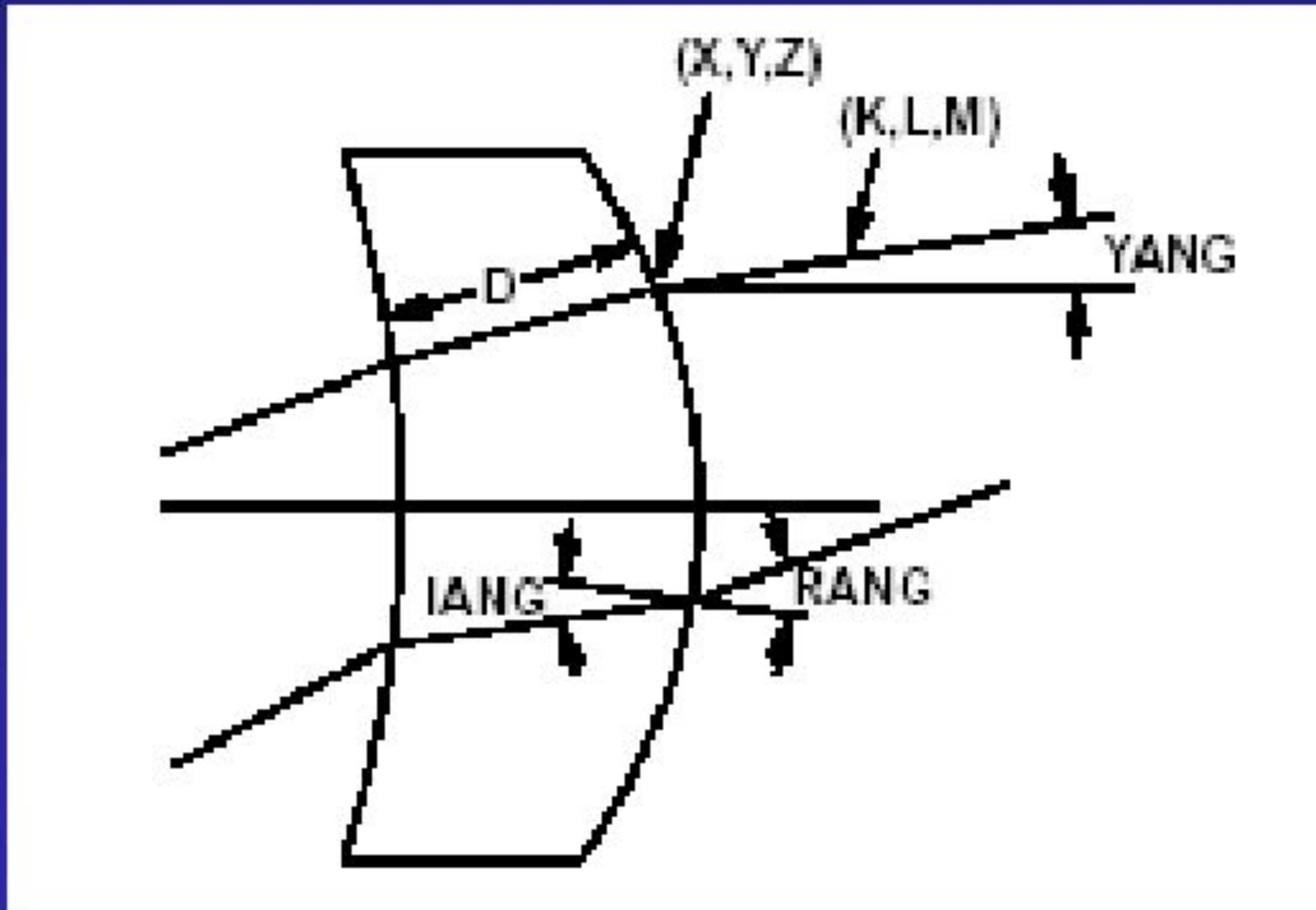
Setting object point

- 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

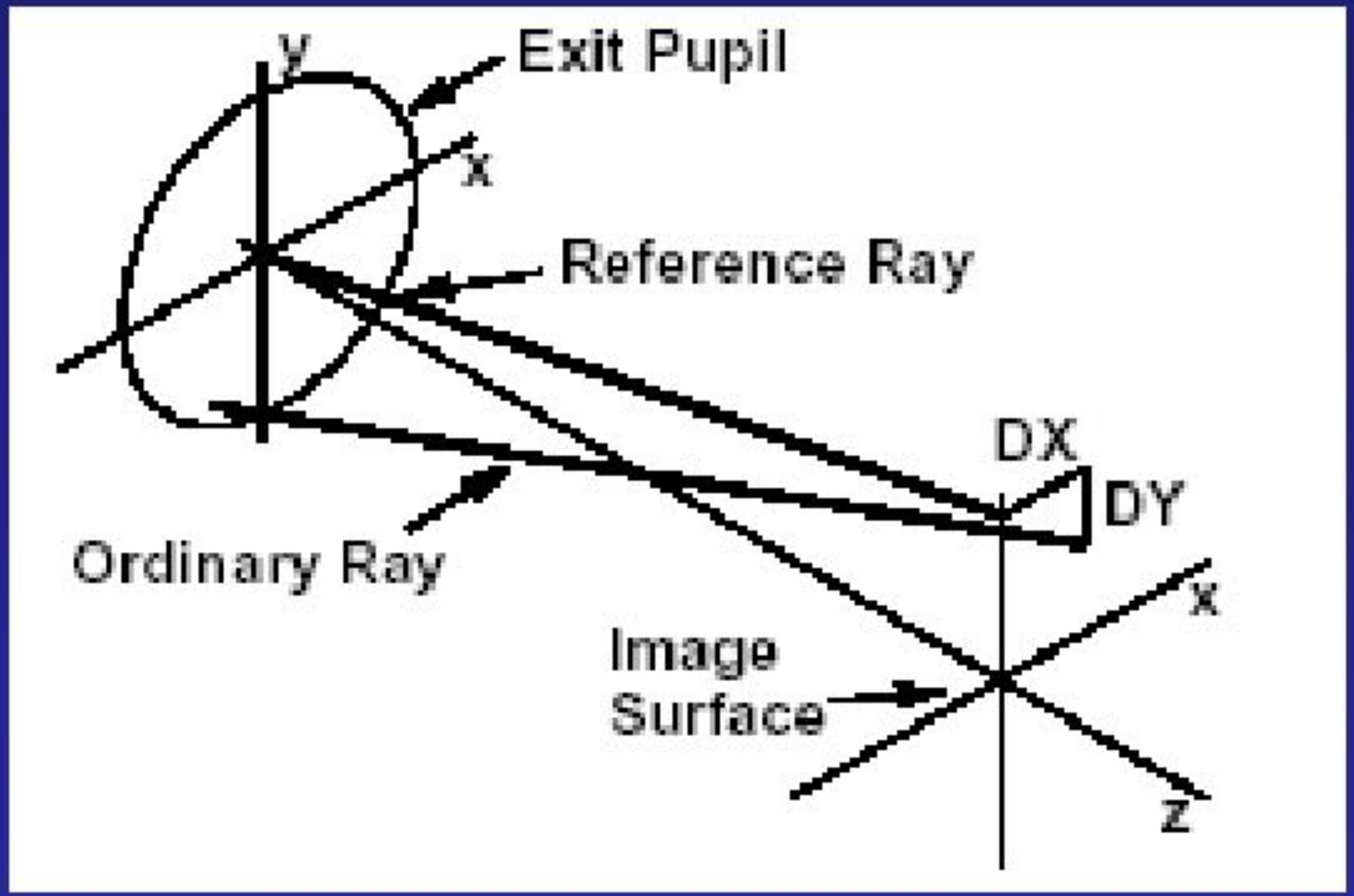


*TRACE RAY - LOCAL COORDS - FBY 1.00, FBX 0.00, FBZ 0.00

SRF	Y/L	X/K	Z/M	YANG/IANG	XANG/RANG	D/OPL
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.

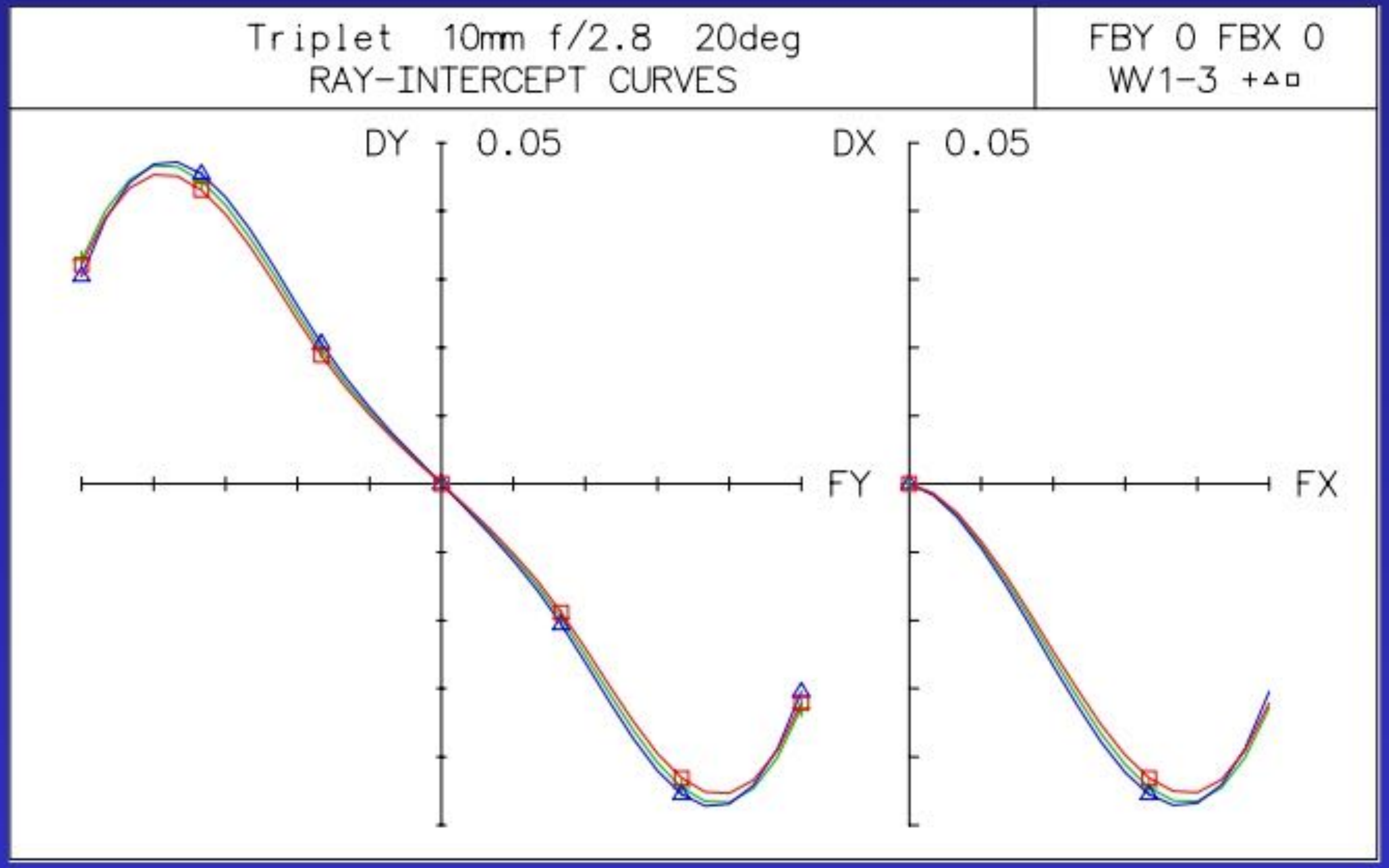


Image quality analysis

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

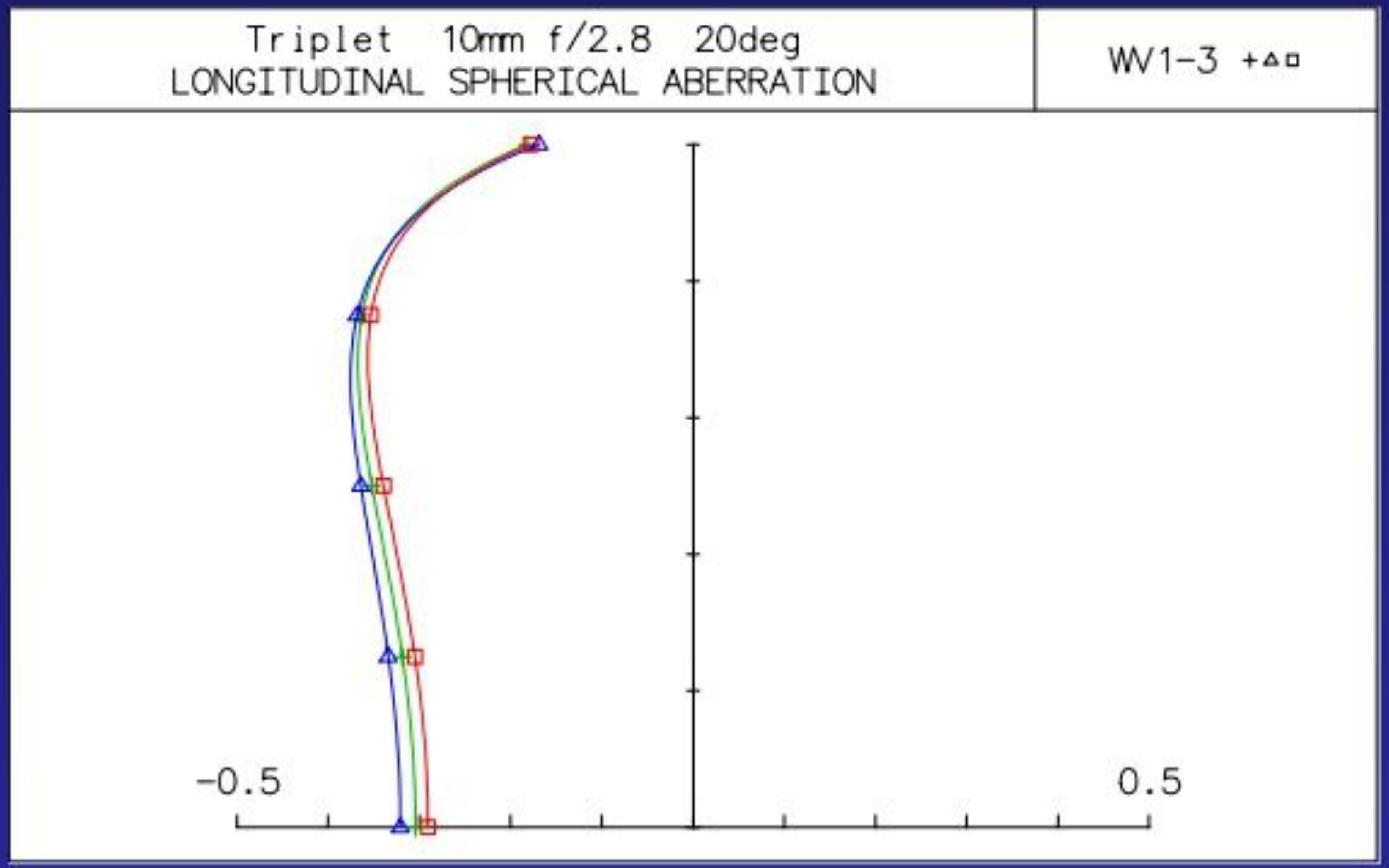
Aberration

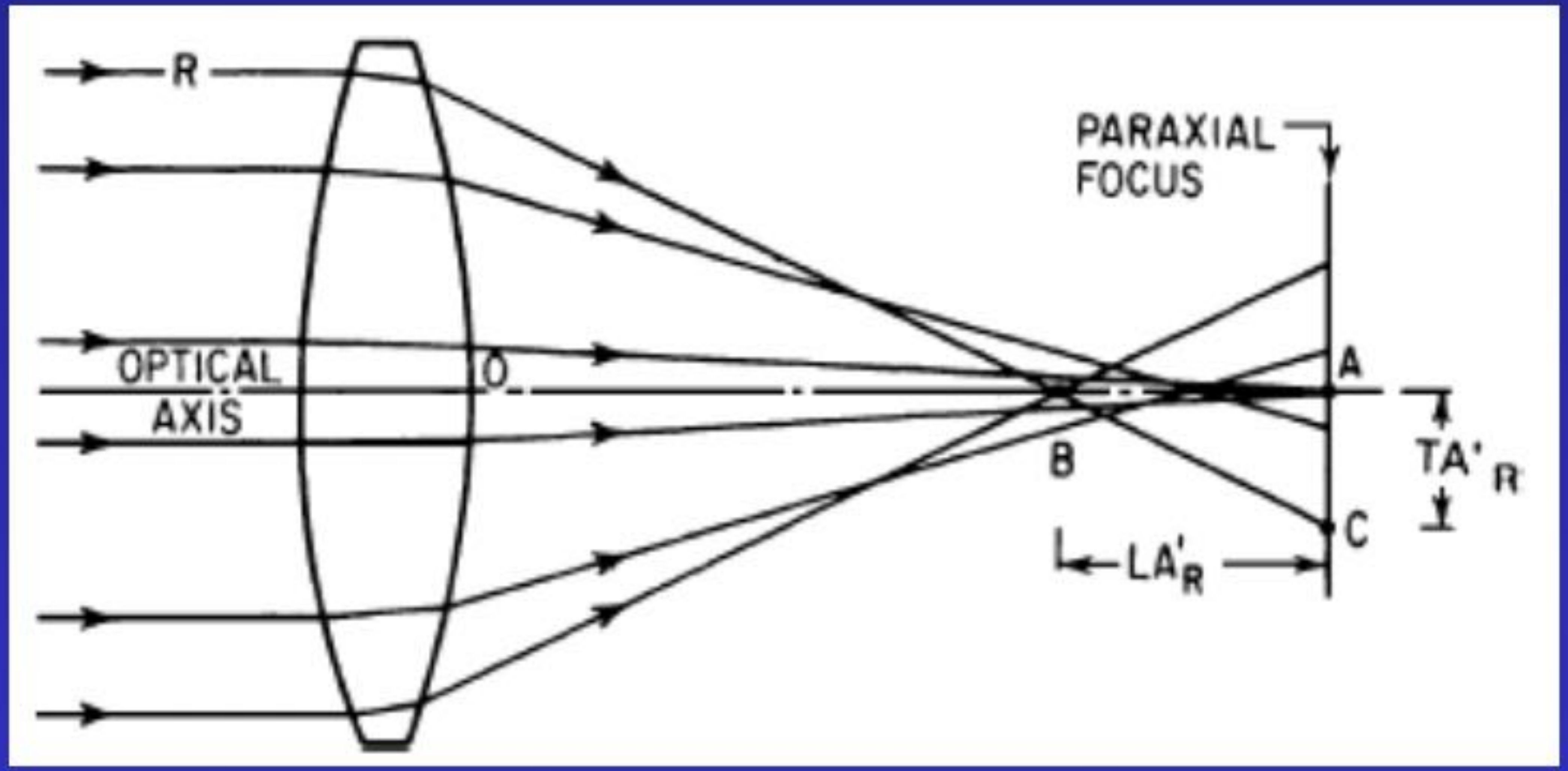
- Spherical aberration
  - Longitudinal spherical aberration

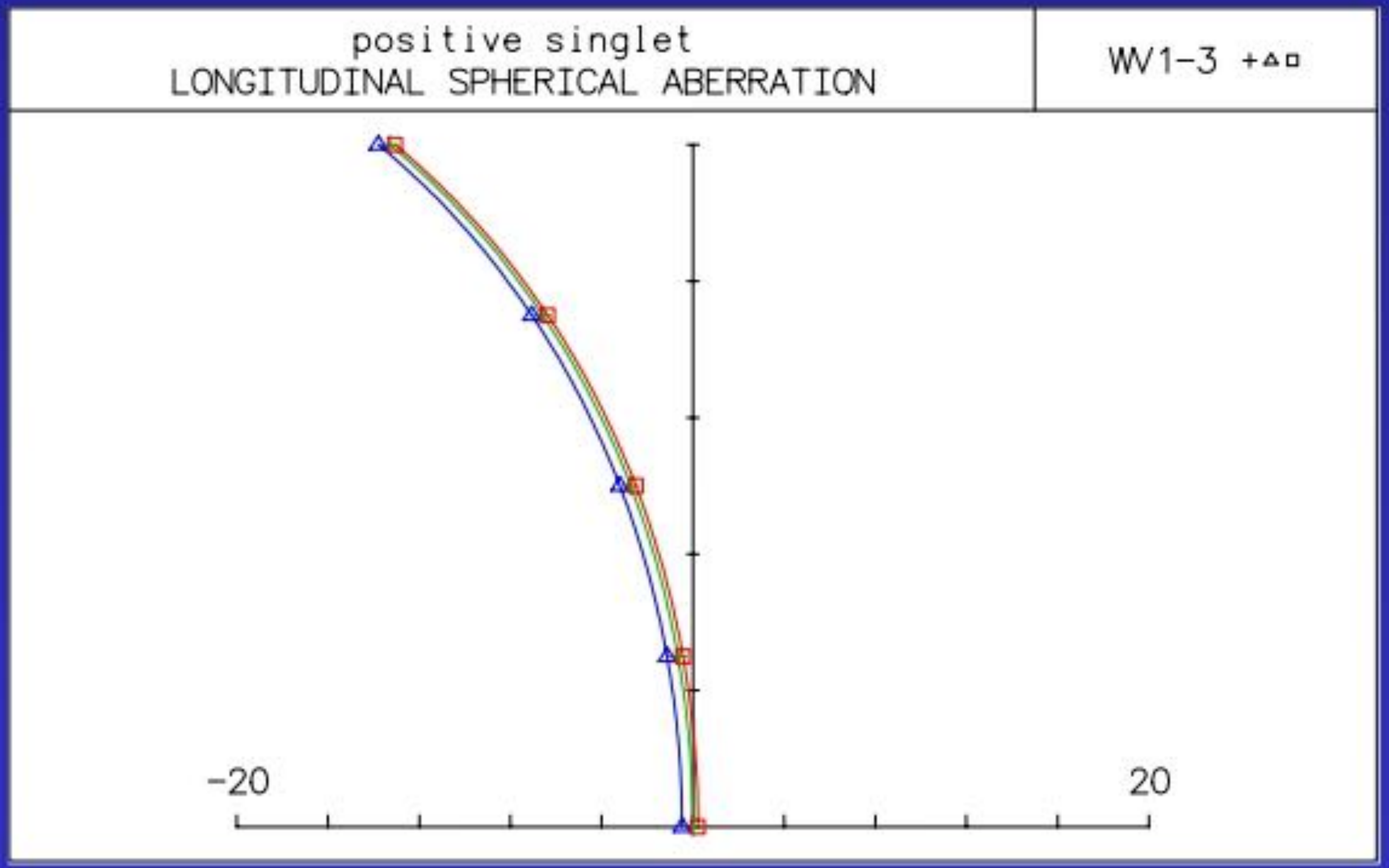
    $$LA_B = L - l$$

  - Lateral spherical aberration

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

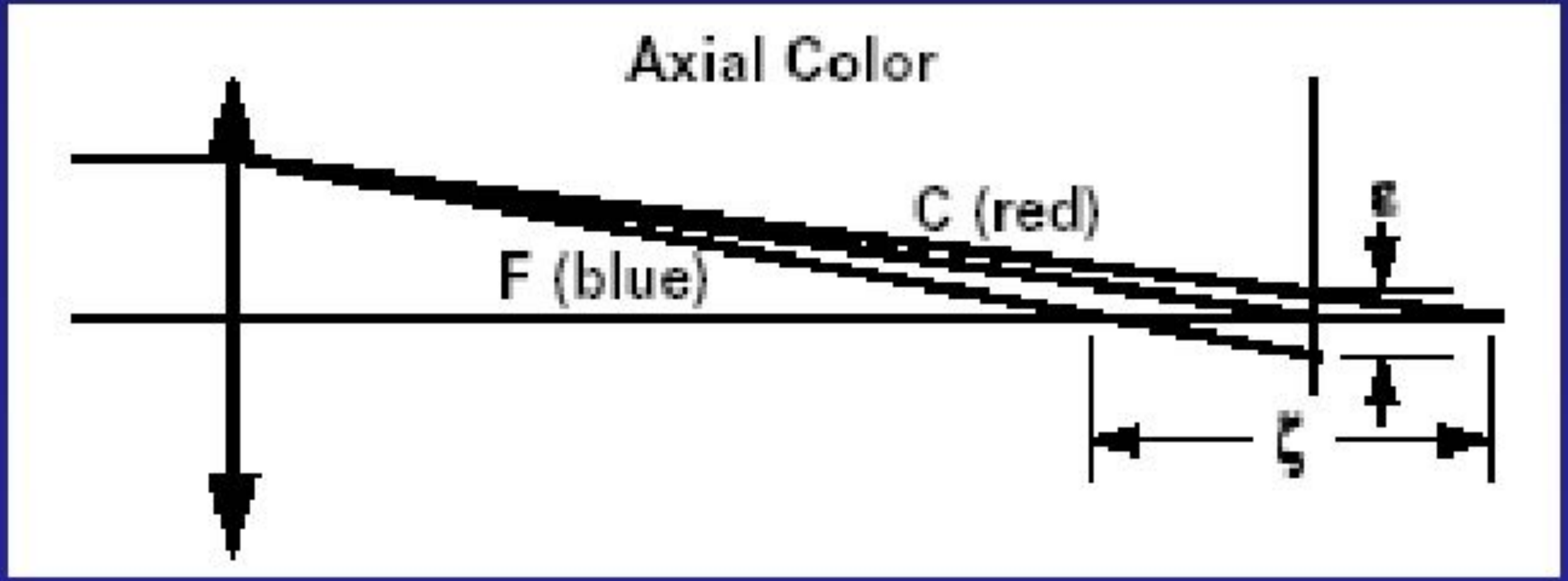


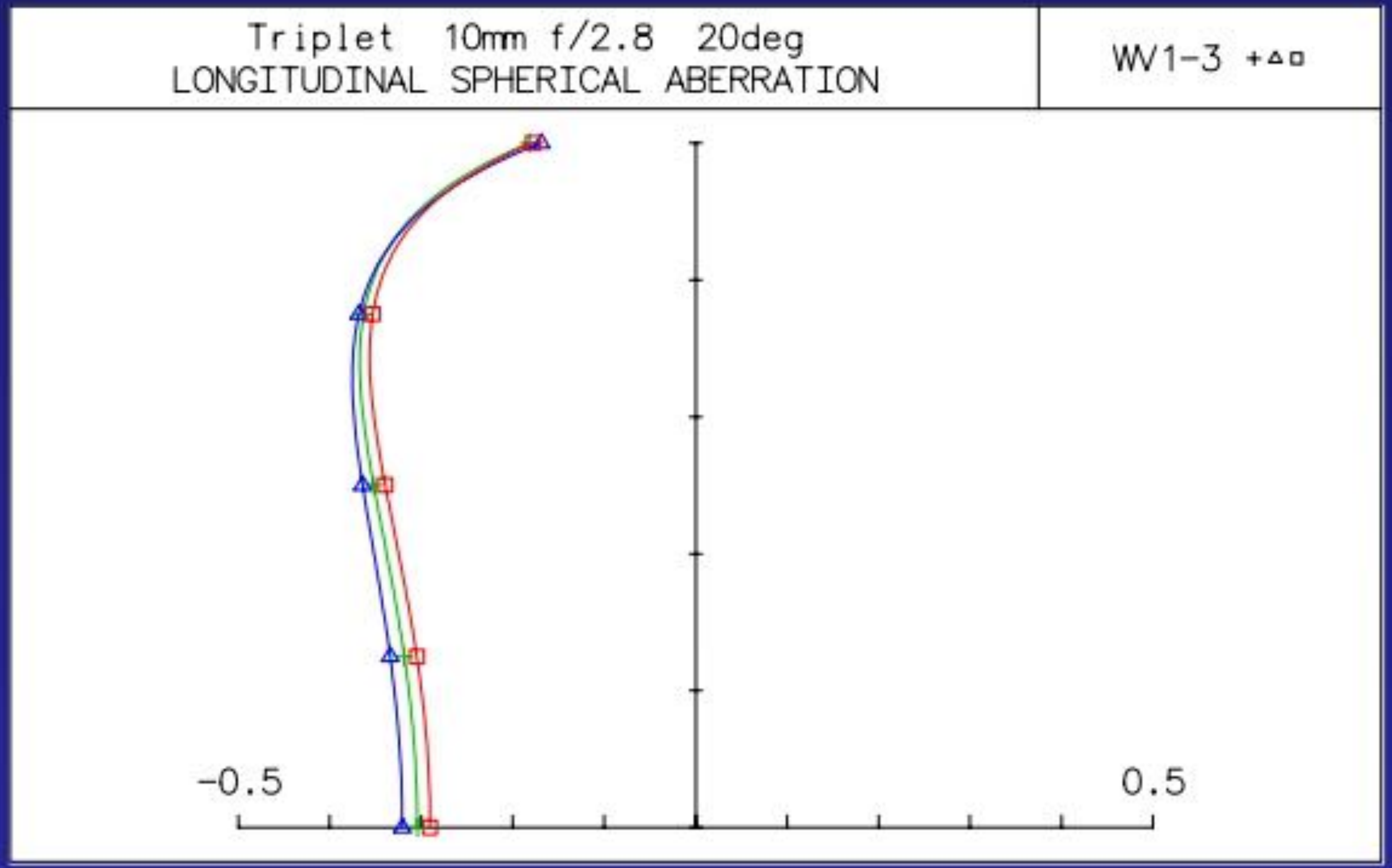




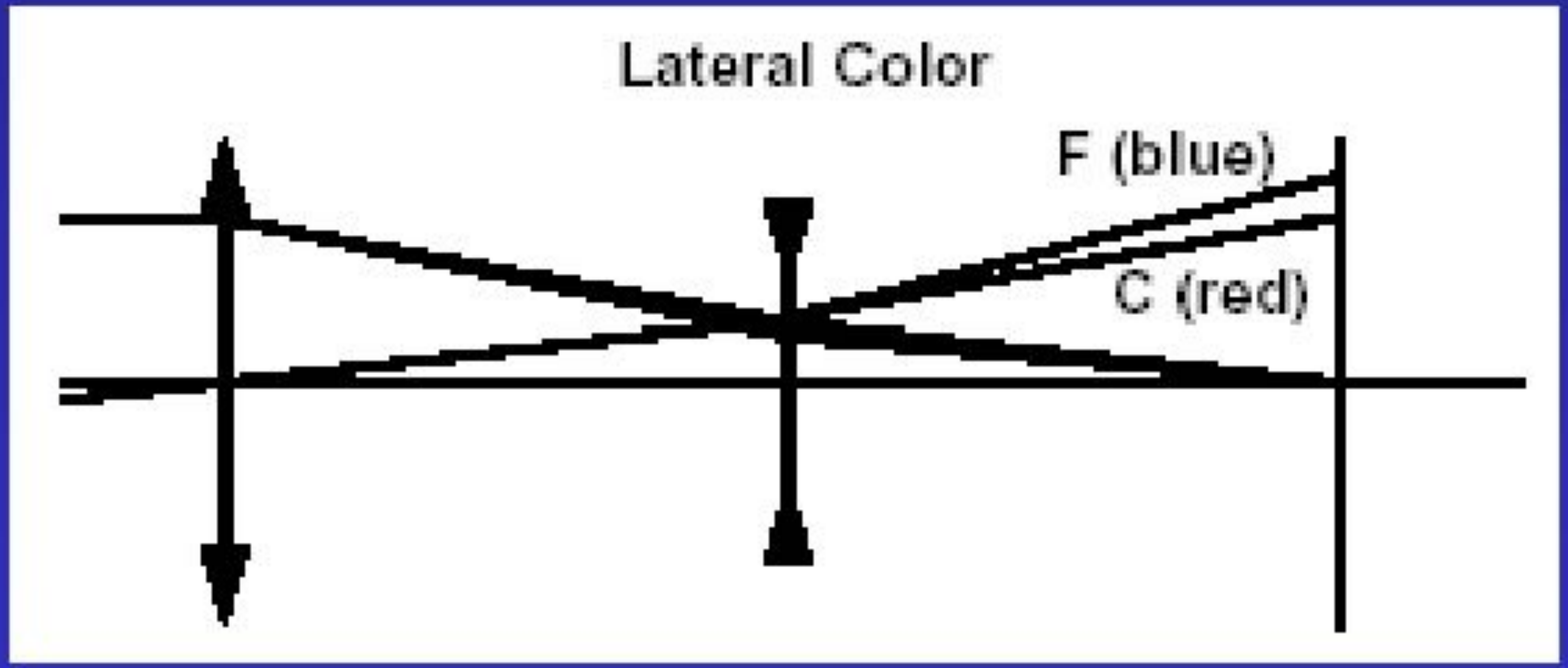
Aberration

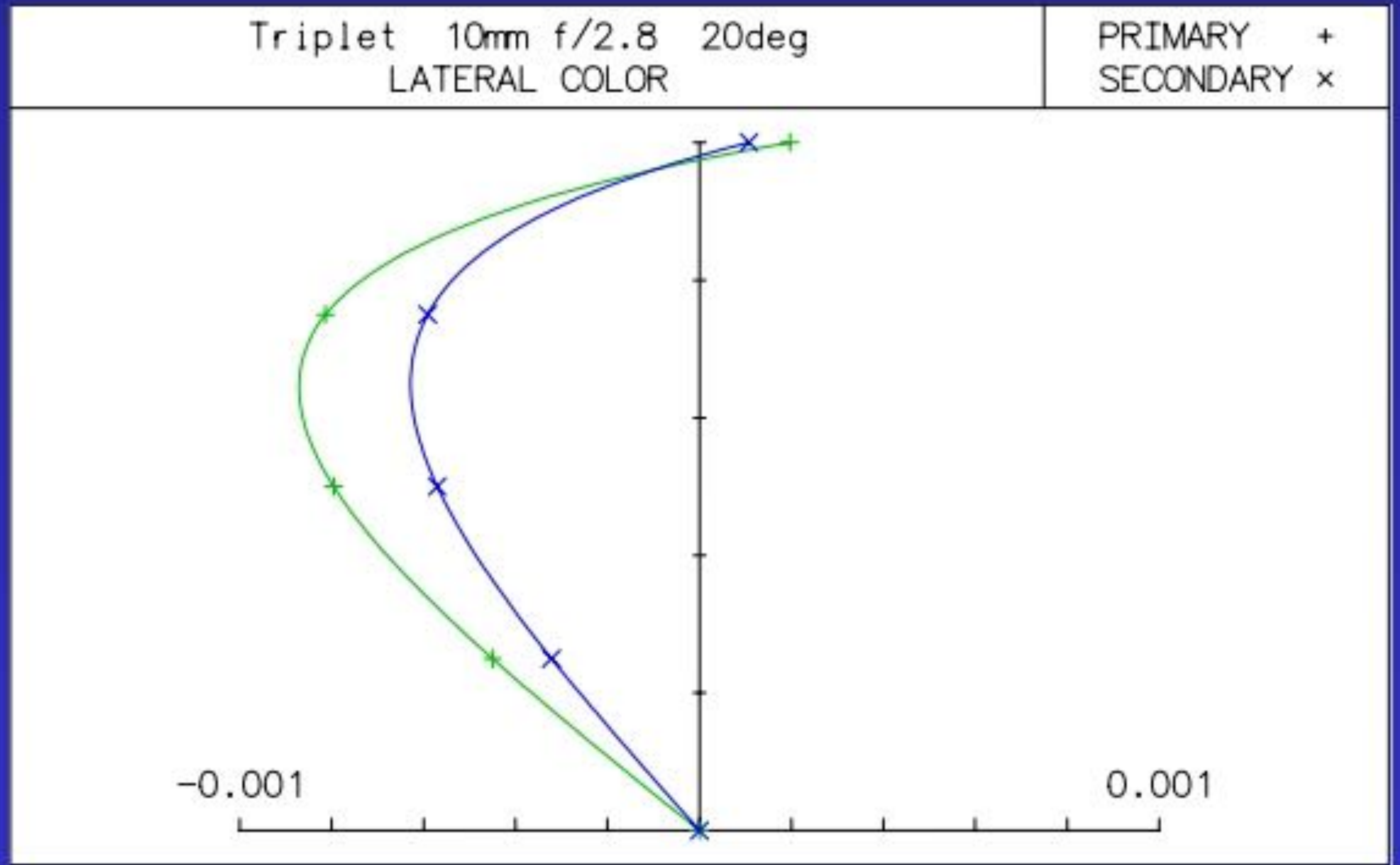
- Chromatic spherical aberration
  - Longitudinal chromatic aberration





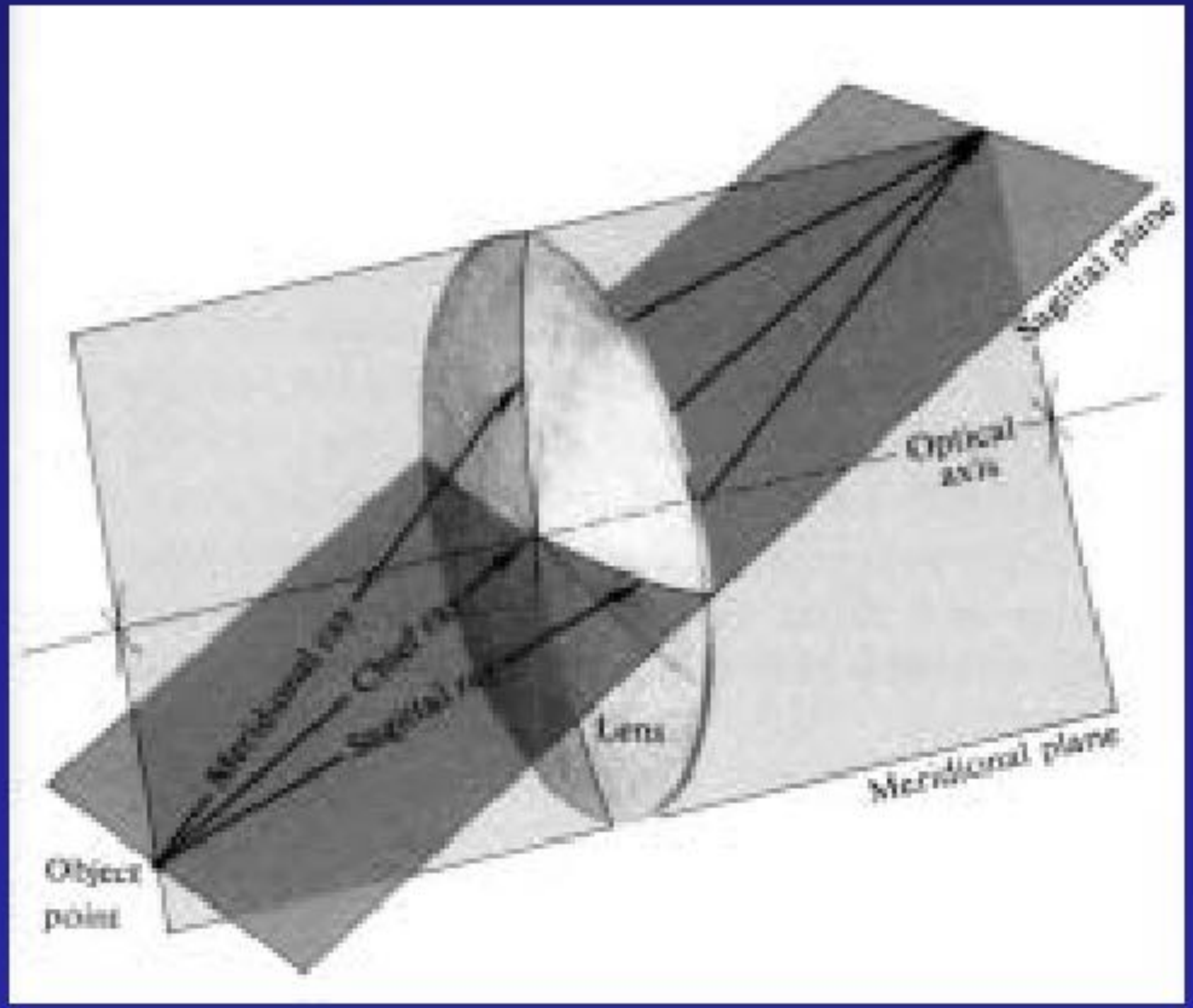
  - Lateral color

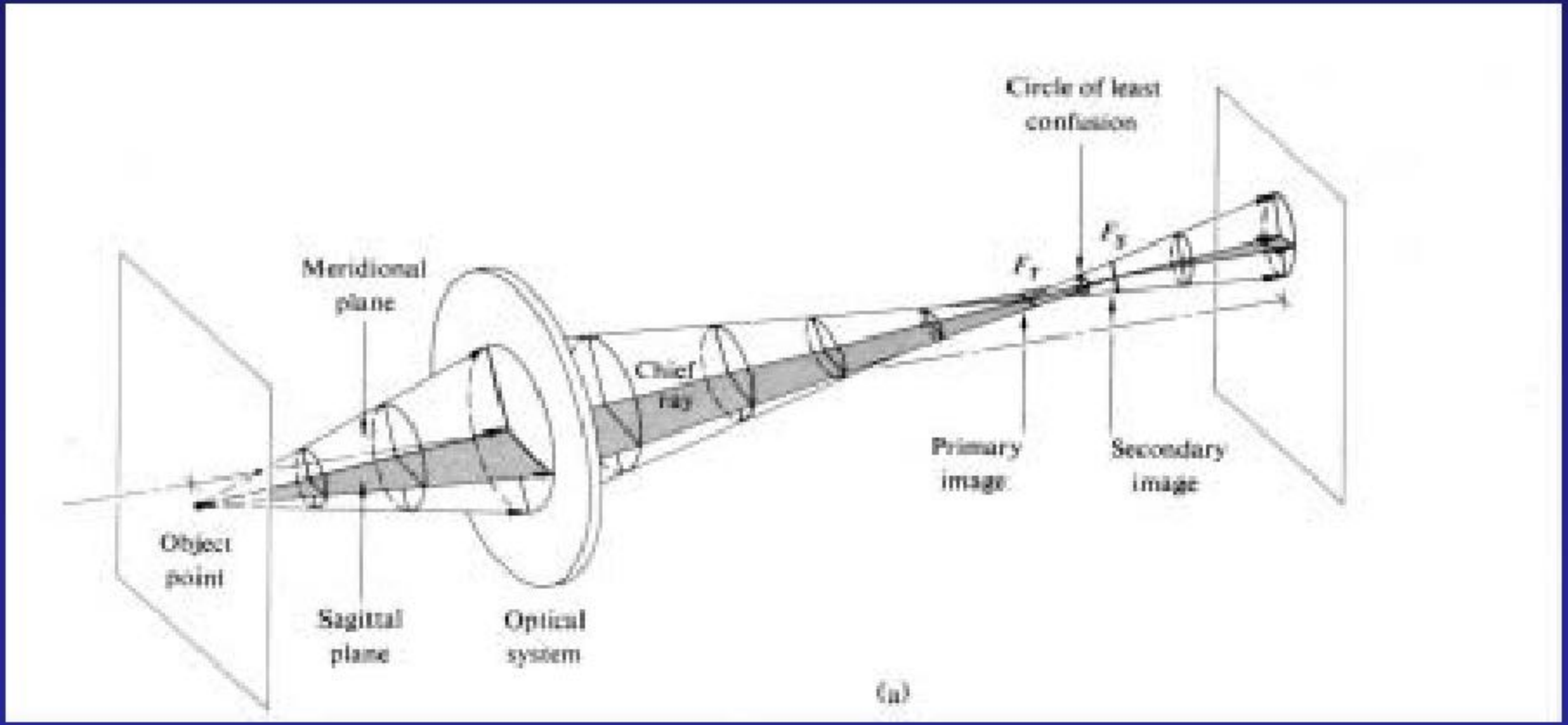


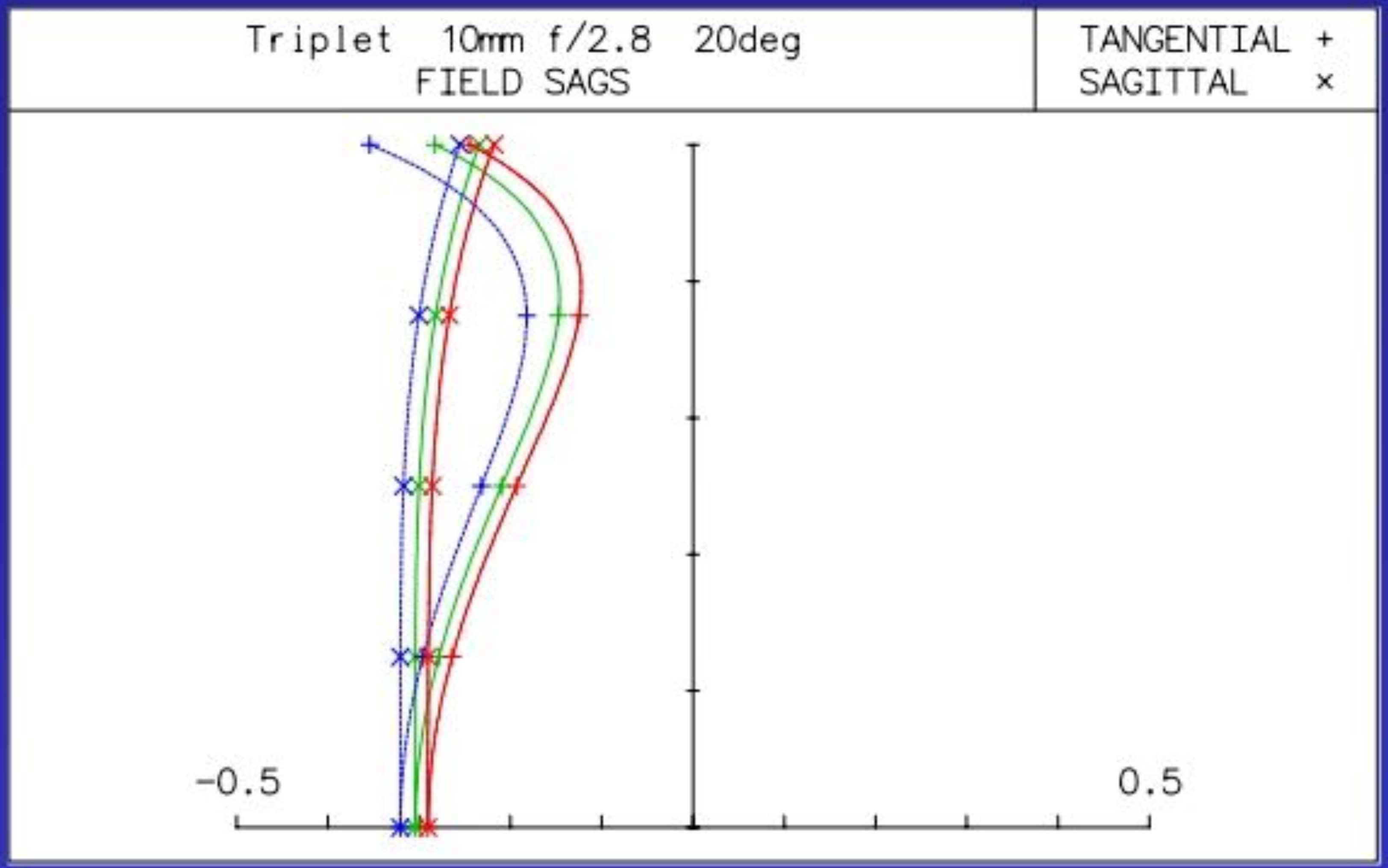


Aberration

- Astigmatism

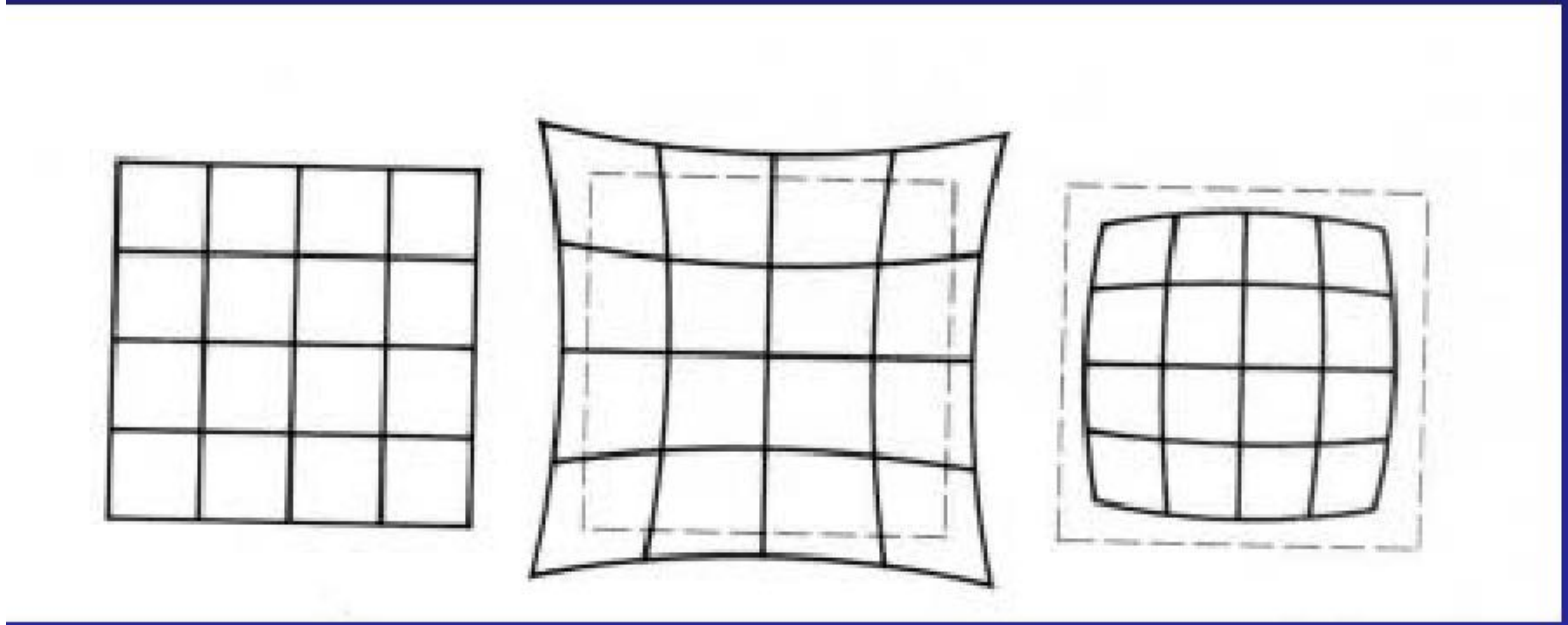


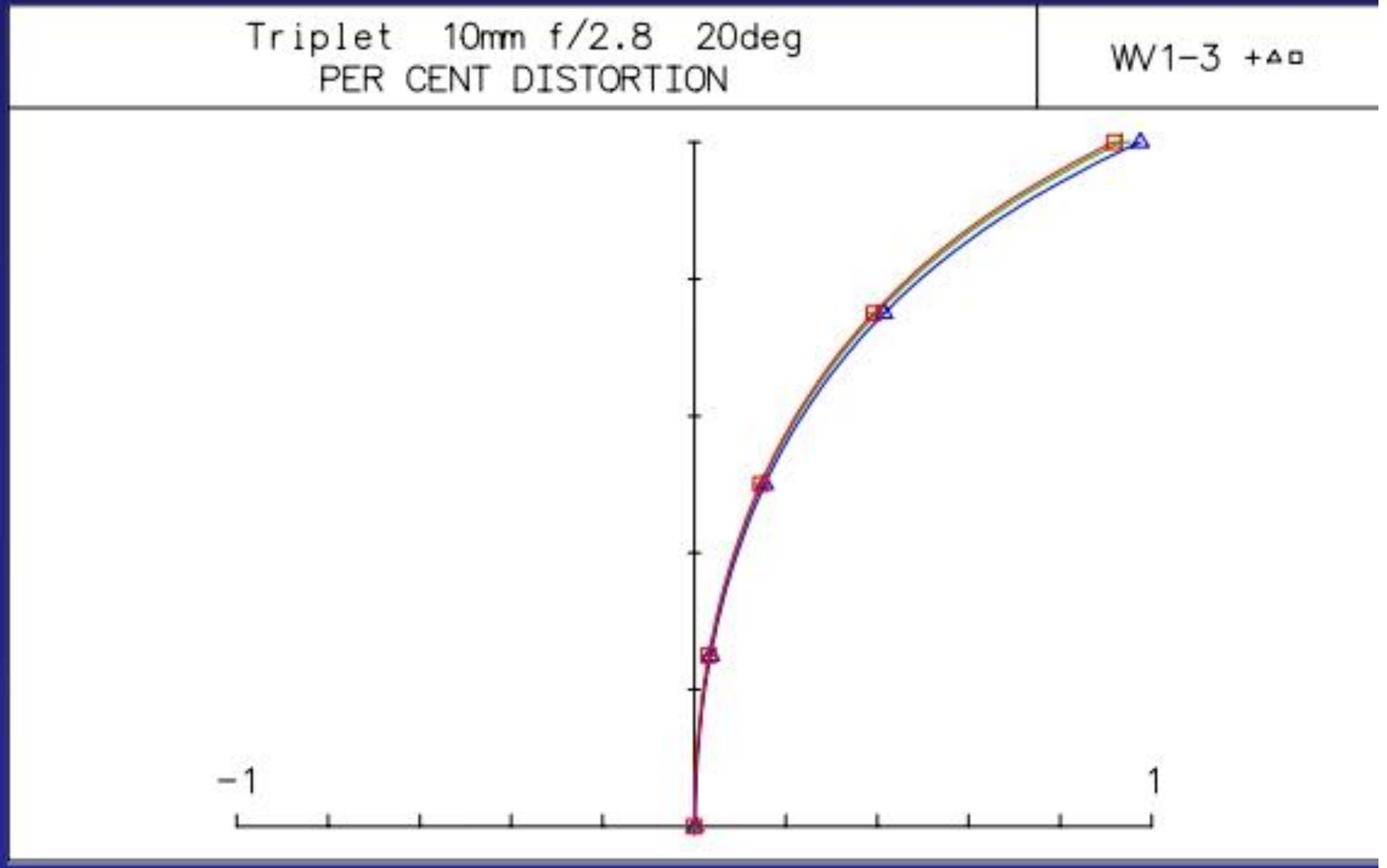


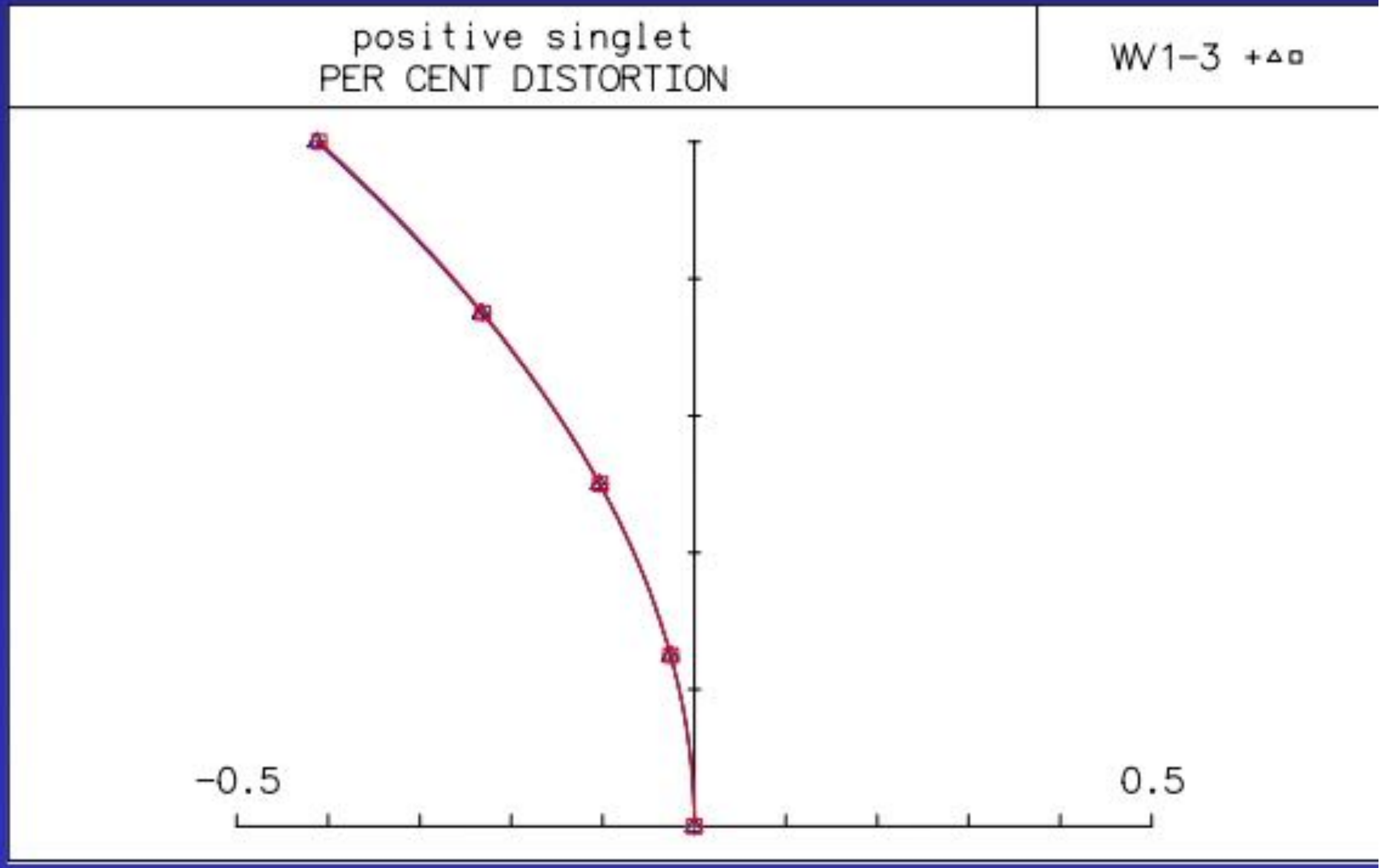


Aberration

- Distortion



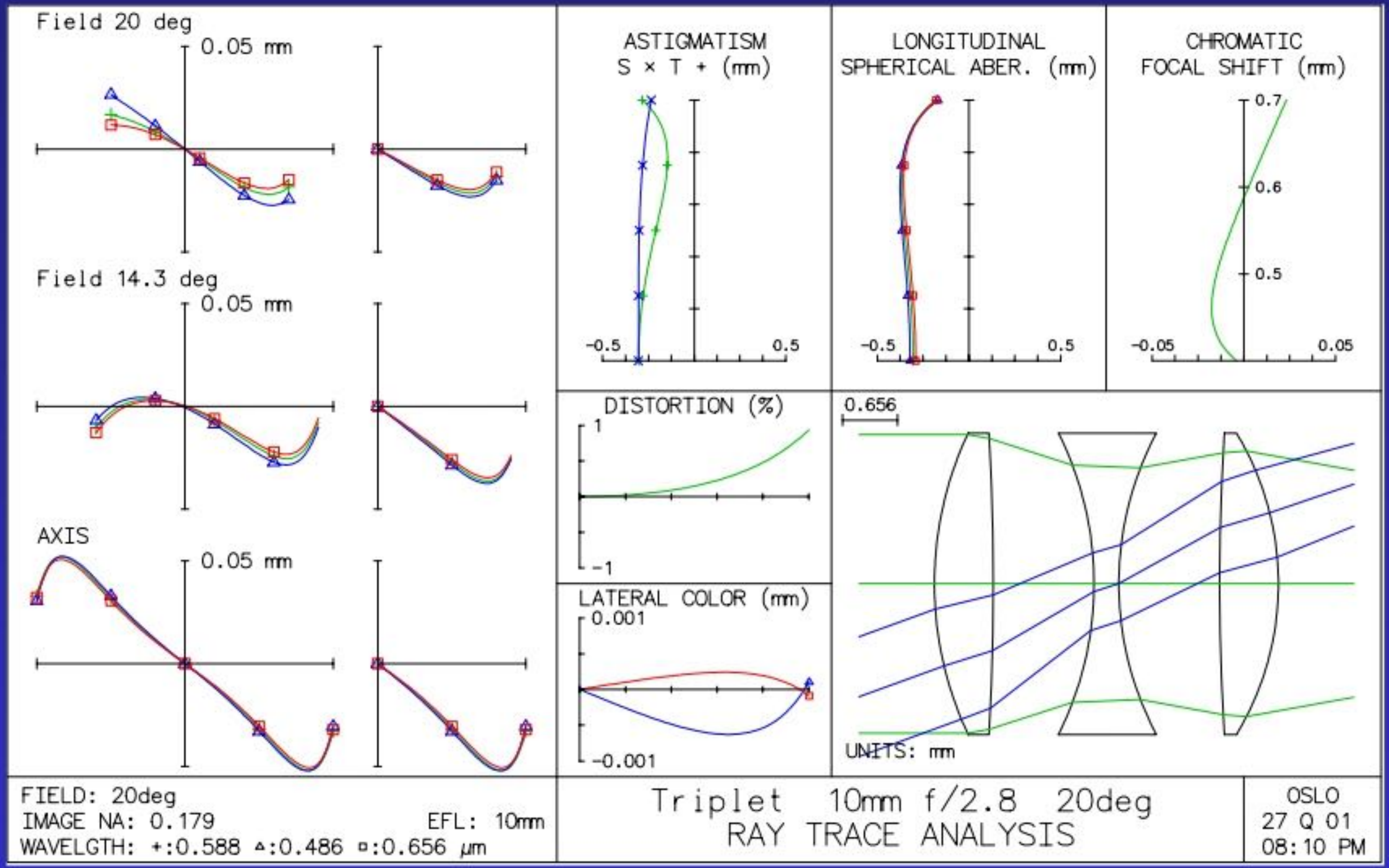




  - distortion < 0: barrel distortion
  - distortion > 0: pincushion distortion

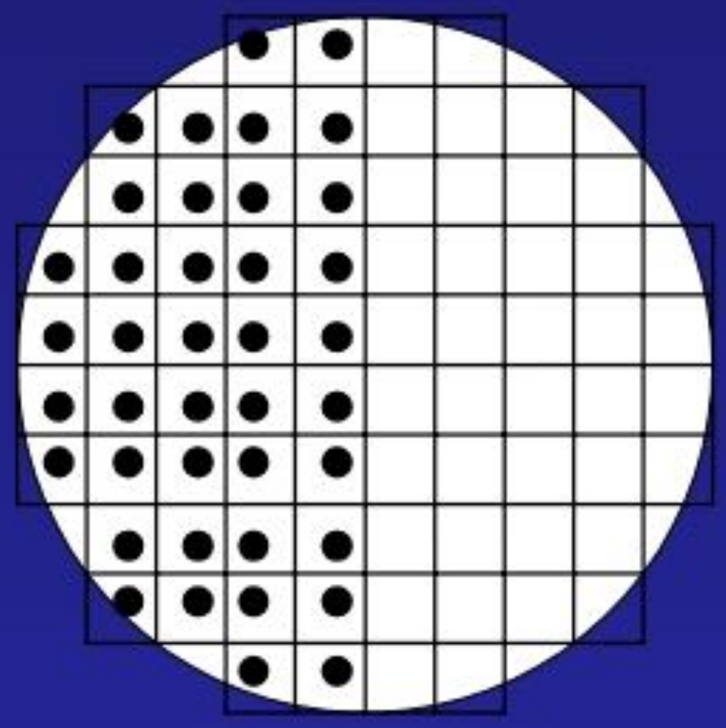
Report graphs of Ray analysis

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

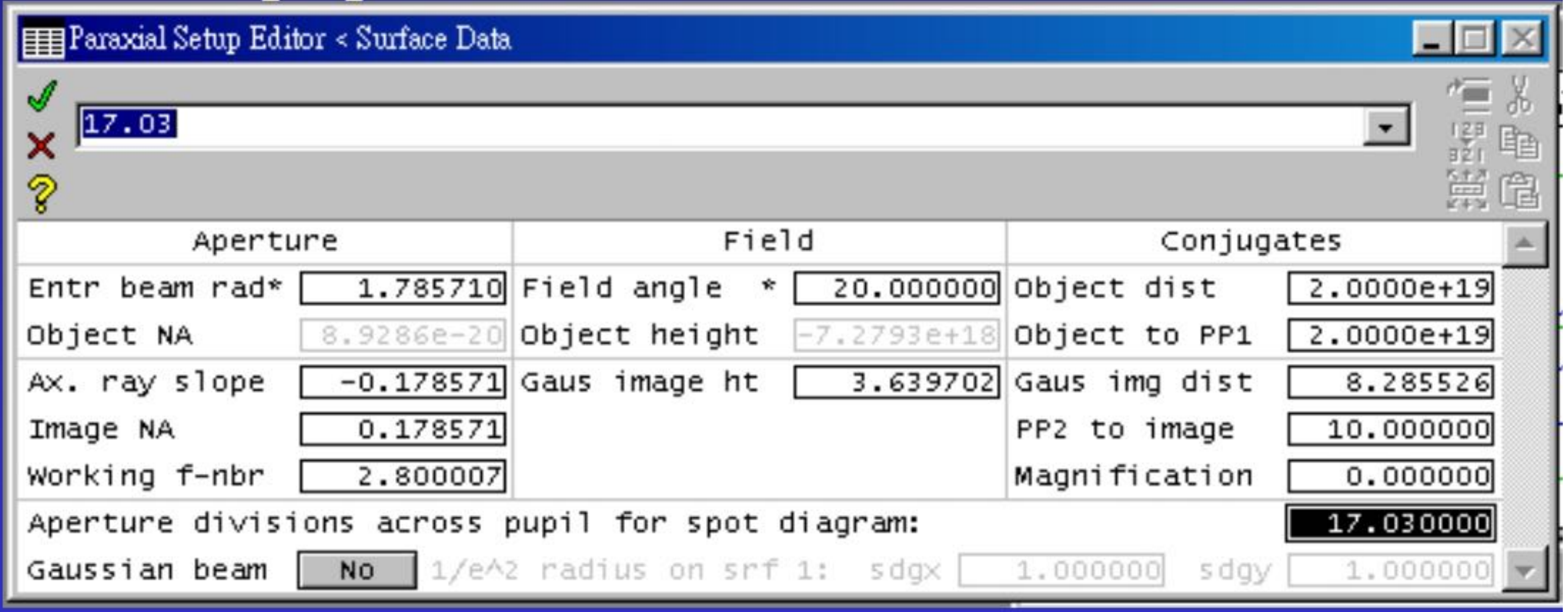


Spot diagram

- A collection of ray data resulting from tracing a large number of rays from a single object point through the aperture of the lens.

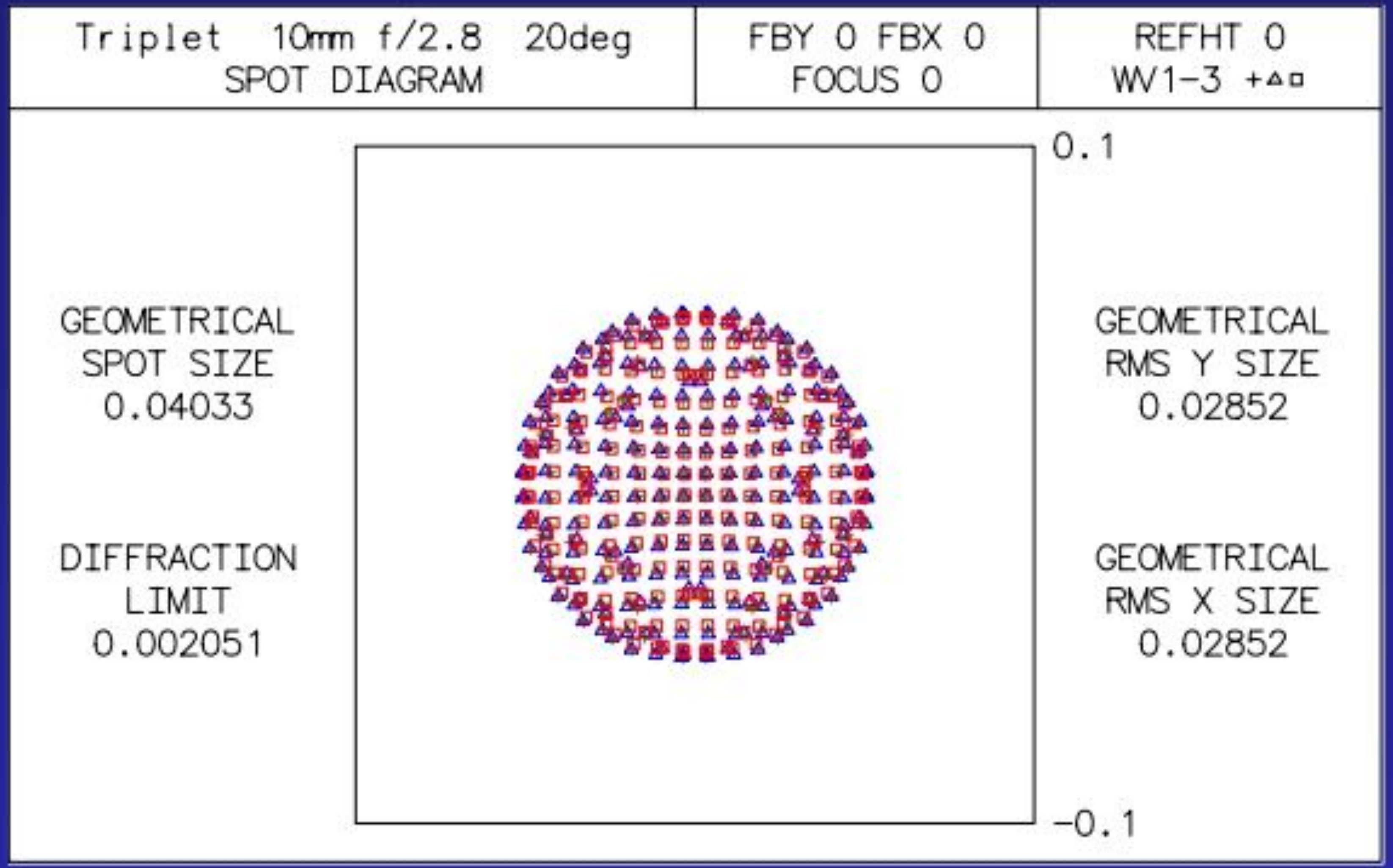


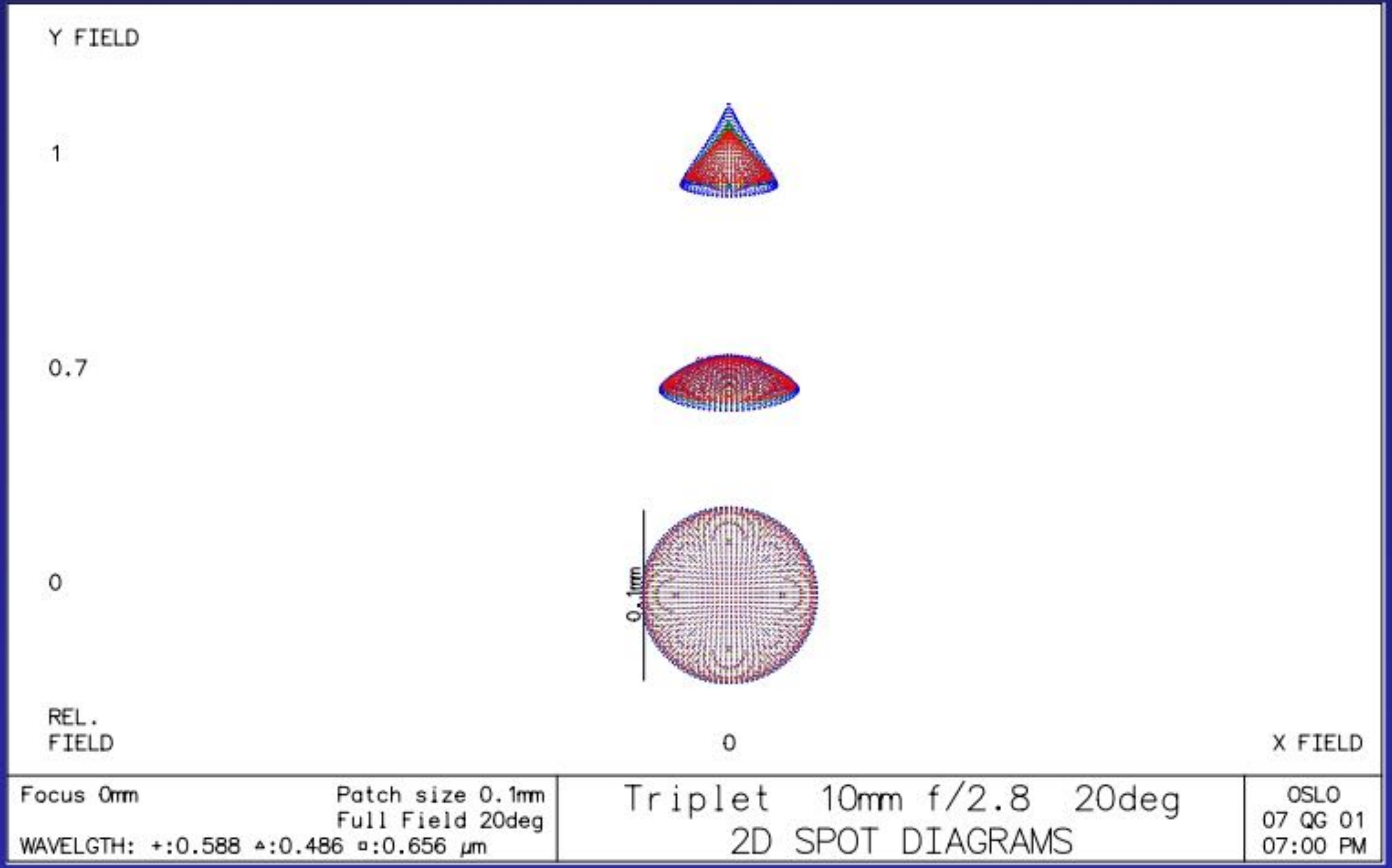
- In OSLO, the rays that trace for a spot diagram is distributed in a ***square grid*** in ***entrance pupil***. The parameter is set in the Setup spreadsheet.



Spot diagram

- Graphic output





Spot diagram

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

*SPOT SIZES

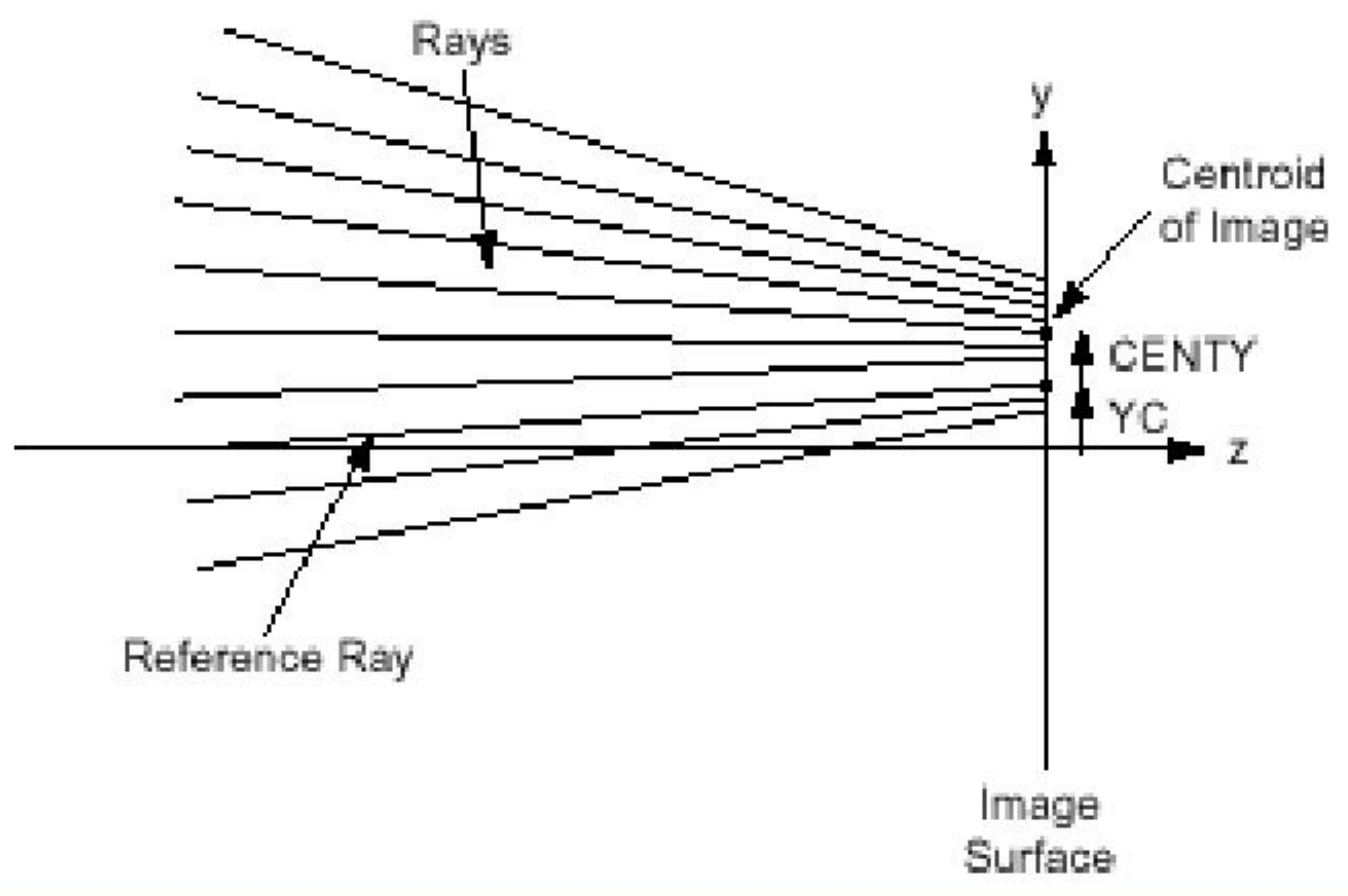
GEO RMS Y	GEO RMS X	GEO RMS R	DIFFR LIMIT	CENTY	CENTX
0.028518	0.028518	0.040330	0.002051	--	--

σ_x σ_y σ_r

$$\sigma_x^2 = \frac{1}{W}\sum_{i=1}^{n} w_i (DX_i - \langle x \rangle)^2$$

$$\sigma_y^2 = \frac{1}{W}\sum_{i=1}^{n} w_i (DY_i - \langle y \rangle)^2$$

$$\sigma_r = \sqrt{\sigma_x^2 + \sigma_y^2}$$

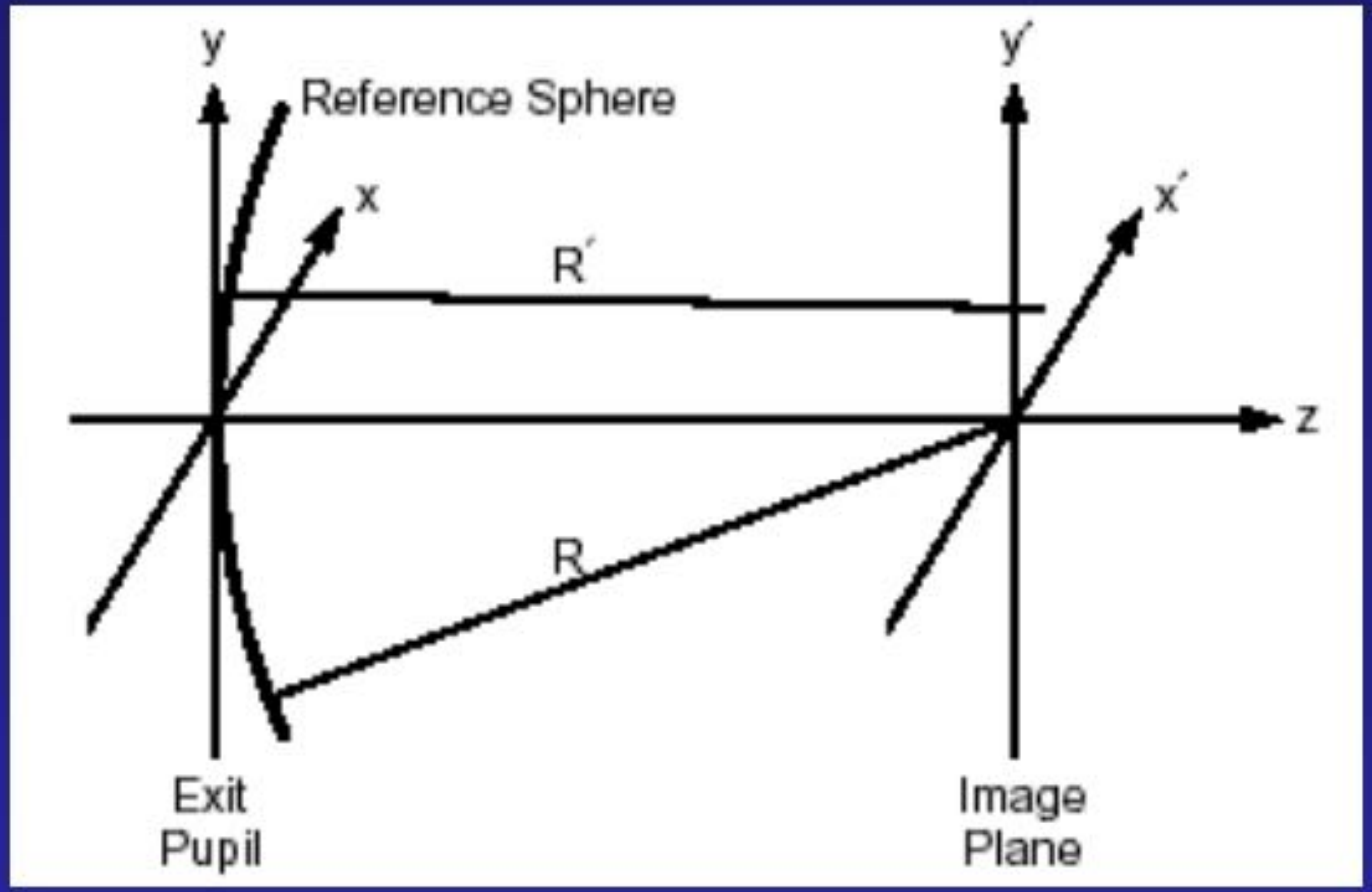


PSF

- 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

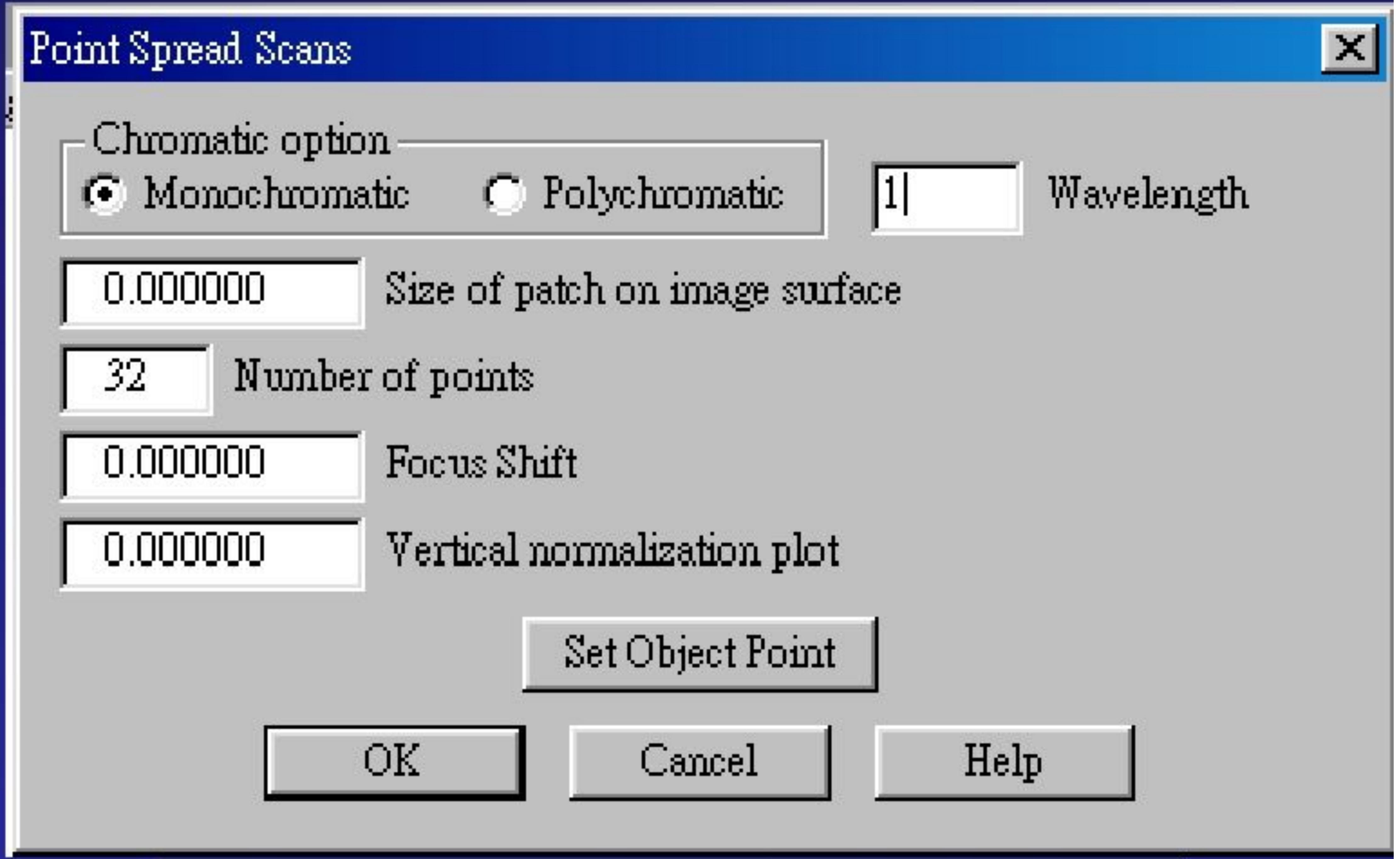
$$PSF(x',y') = \left|U(x',y')\right|^2$$

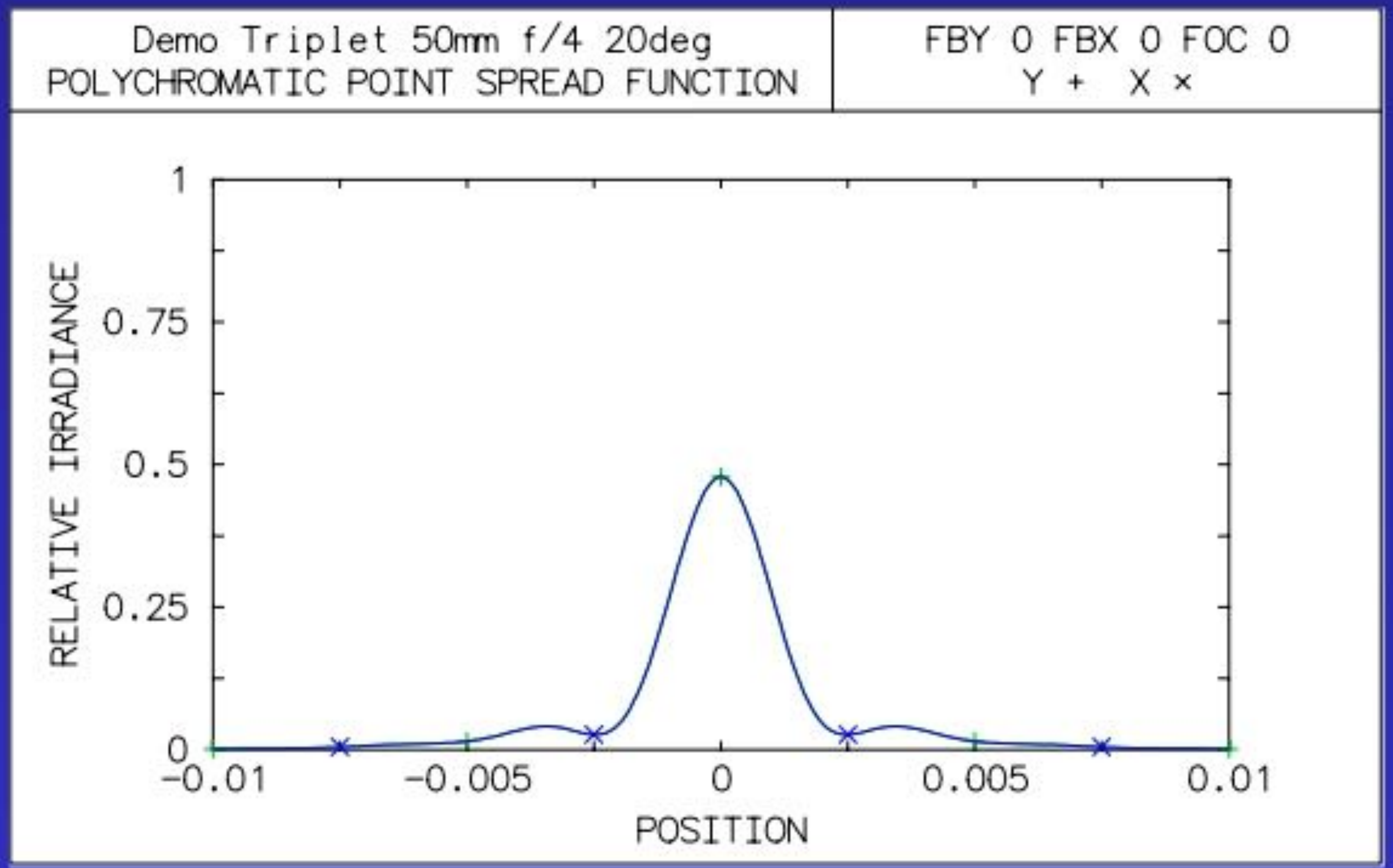
  - The airy disk = diffraction limit

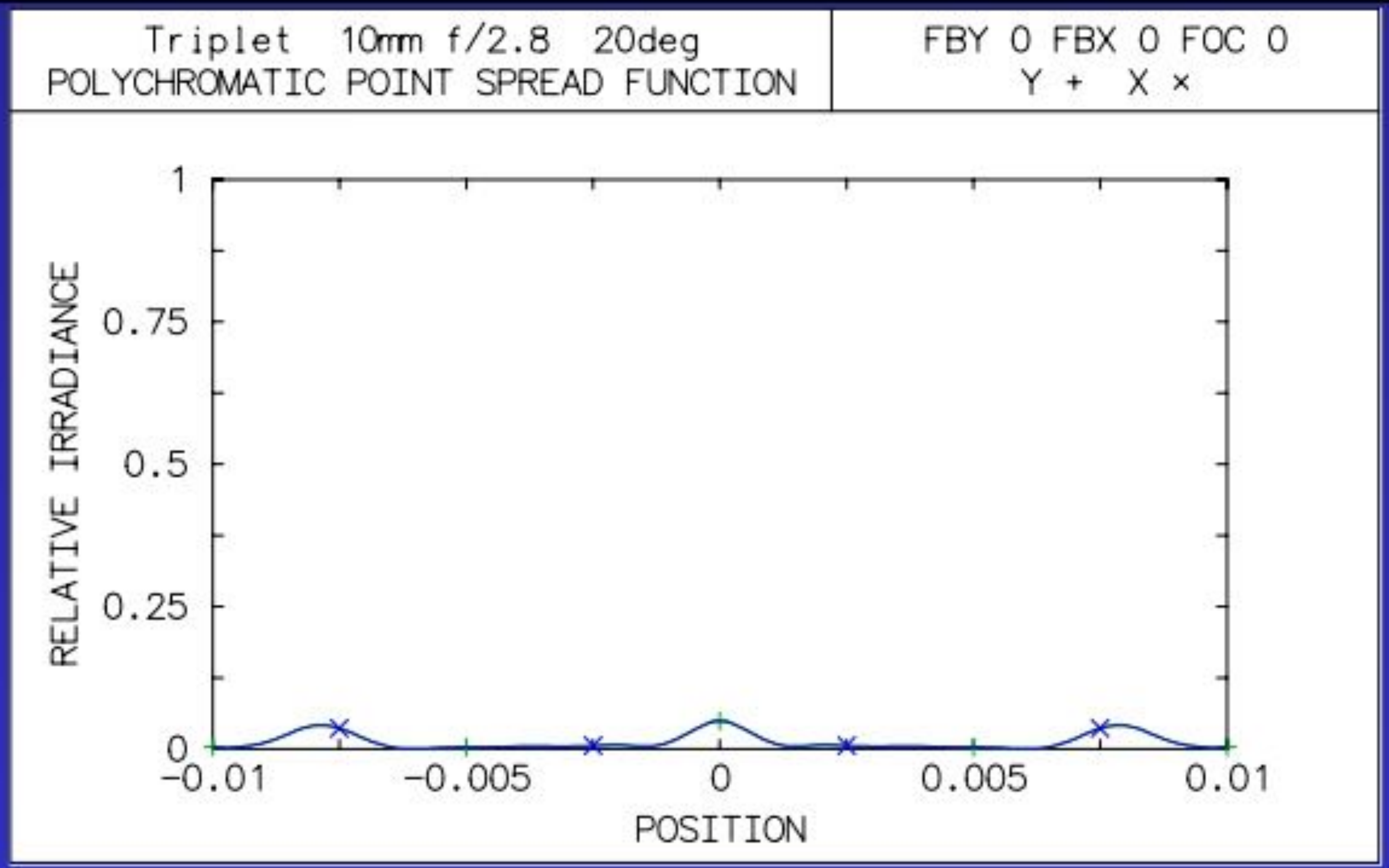
$$r'_{airy} = \frac{0.61\lambda_0}{NA}$$

PSF

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

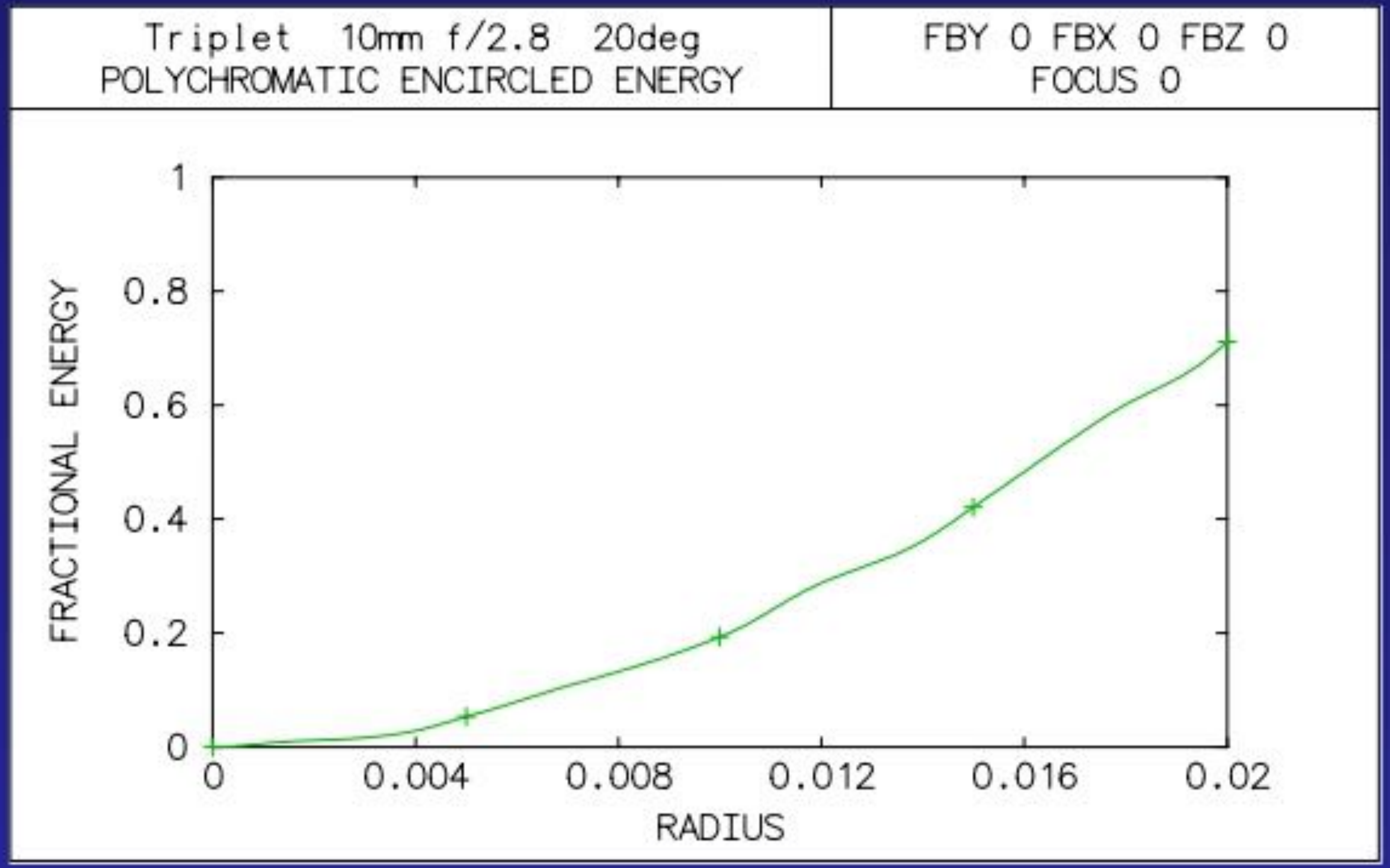


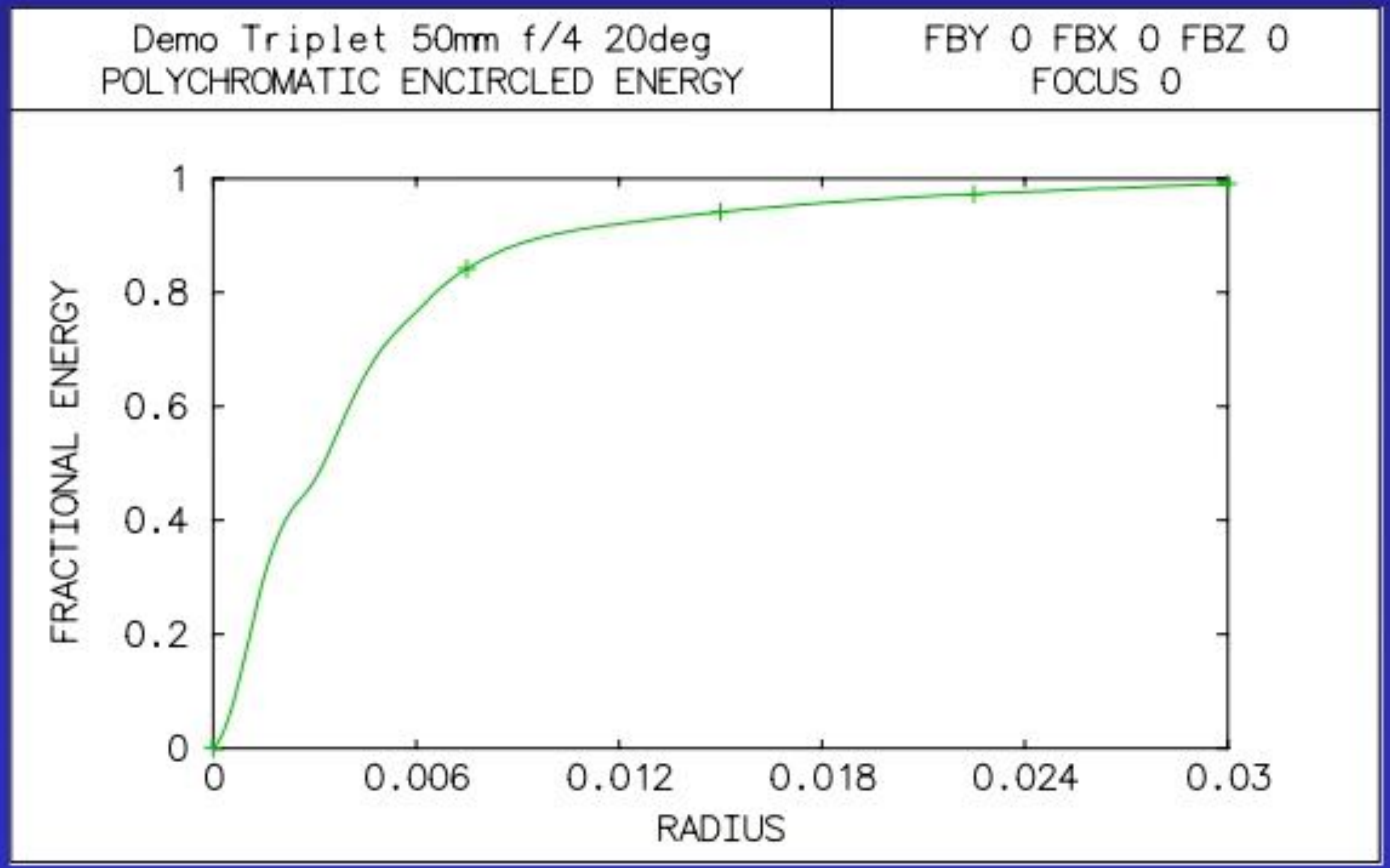


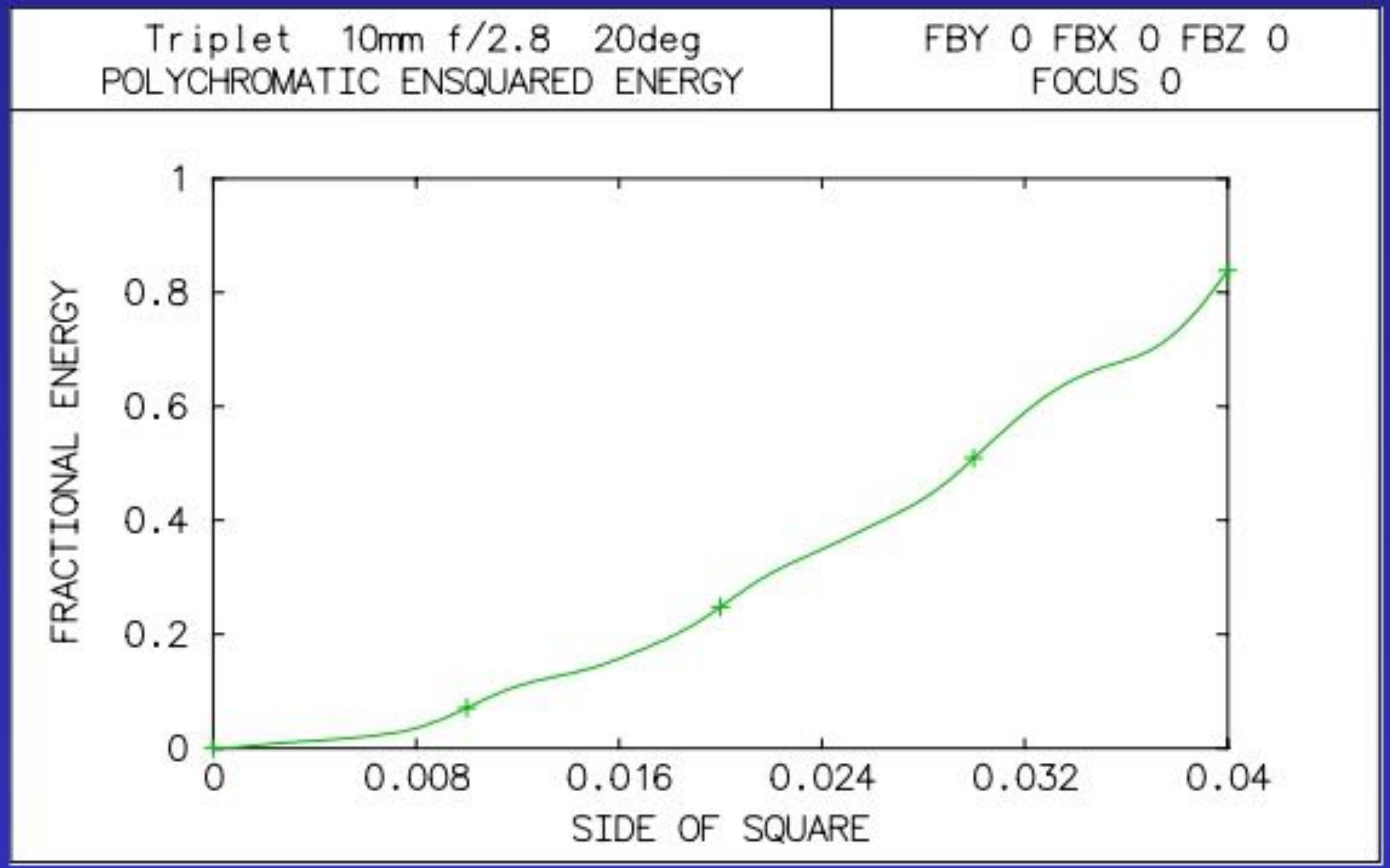


Energy distribution

- 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.





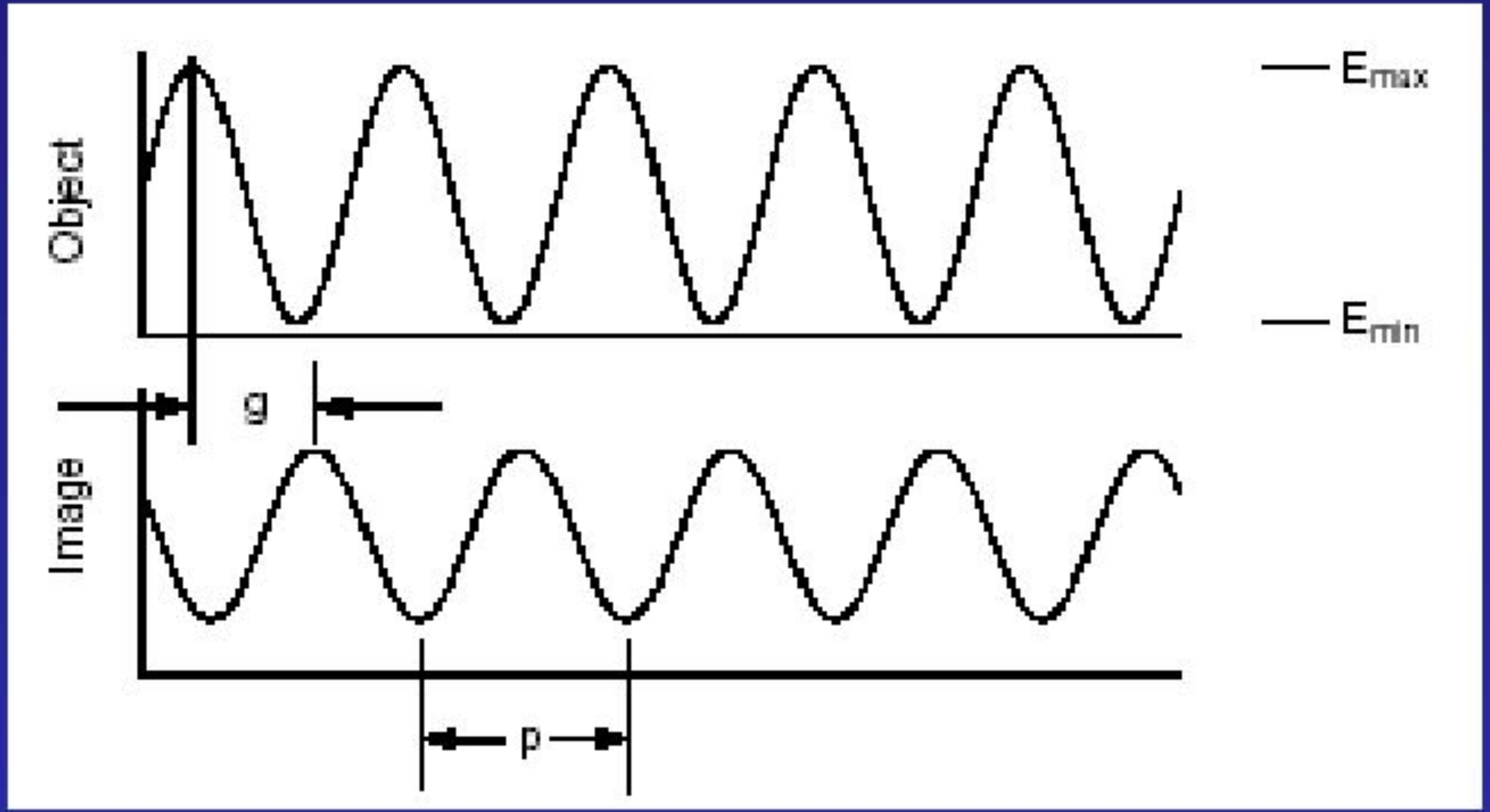


MTF (modulation transfer function)

- 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

$$MTF = \frac{M_{image}}{M_{object}}$$

$$PTF = 2\pi \frac{g}{p} = 2\pi g \nu$$



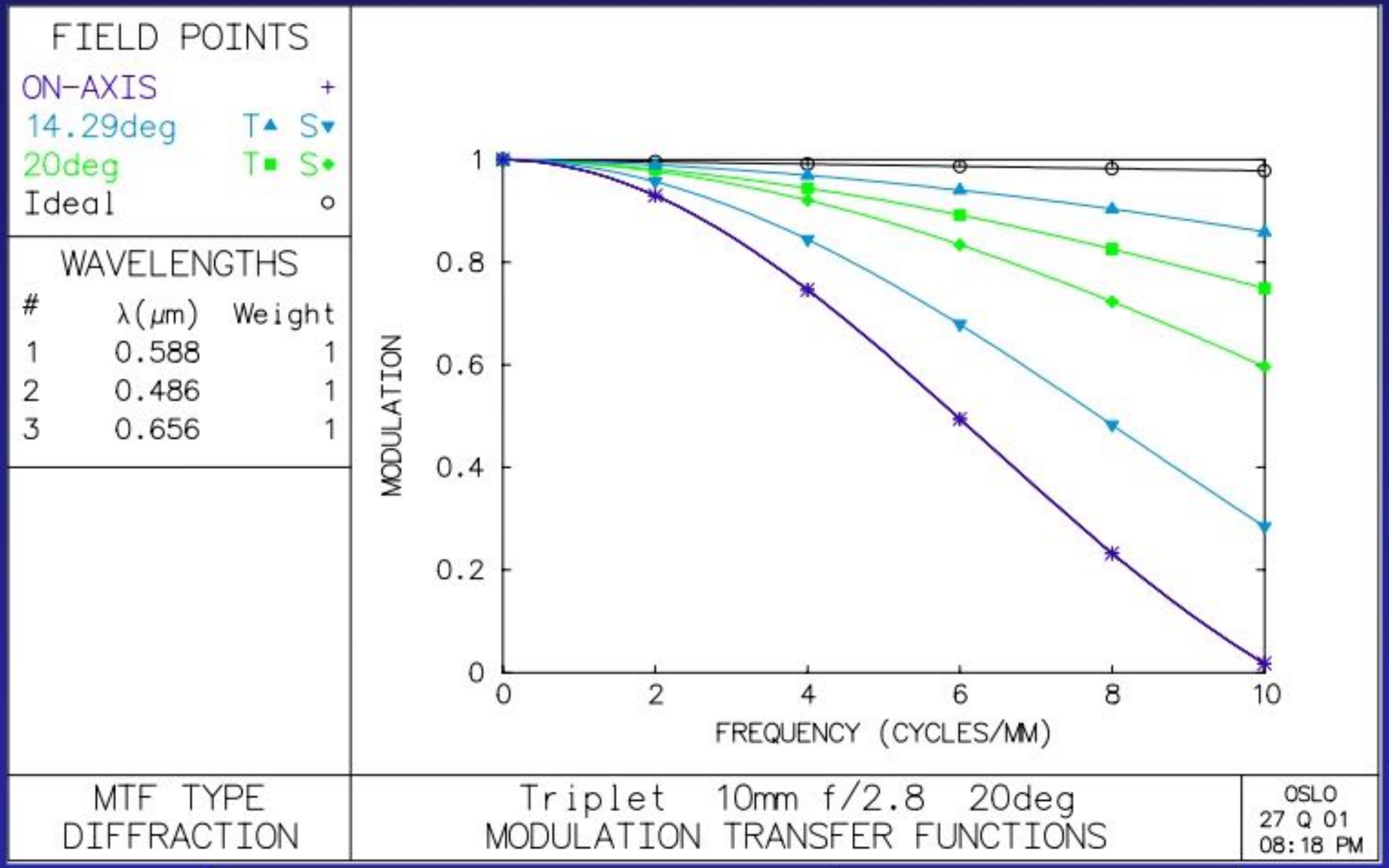
- The object irradiance distribution with Fourier spectrum $O(\nu_x,\nu_y)$ and the Fourier spectrum of the image $I(\nu_x,\nu_y)$ have the form :

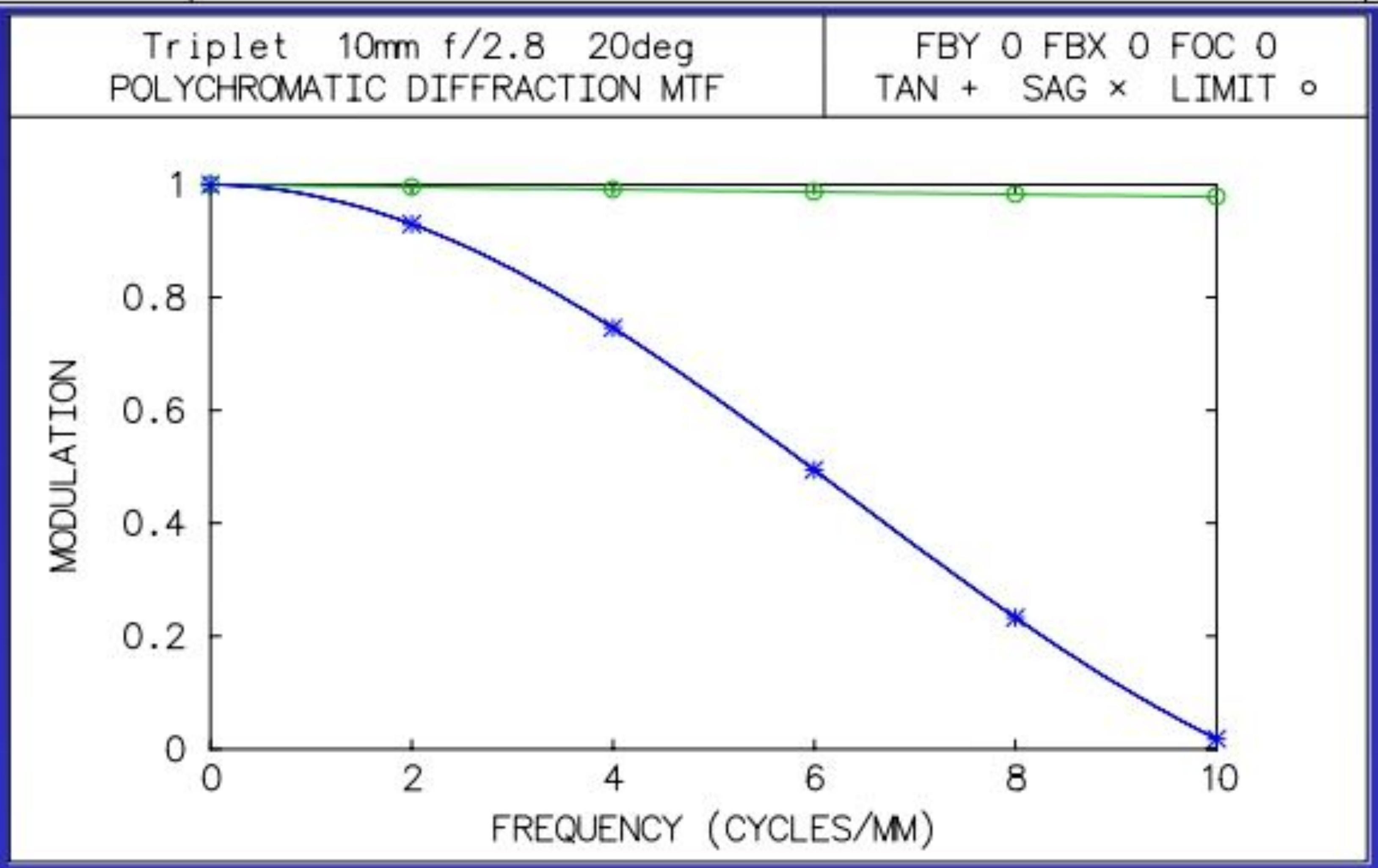
$$I(\nu_x,\nu_y) = OTF(\nu_x,\nu_y)O(\nu_x,\nu_y)$$

MTF

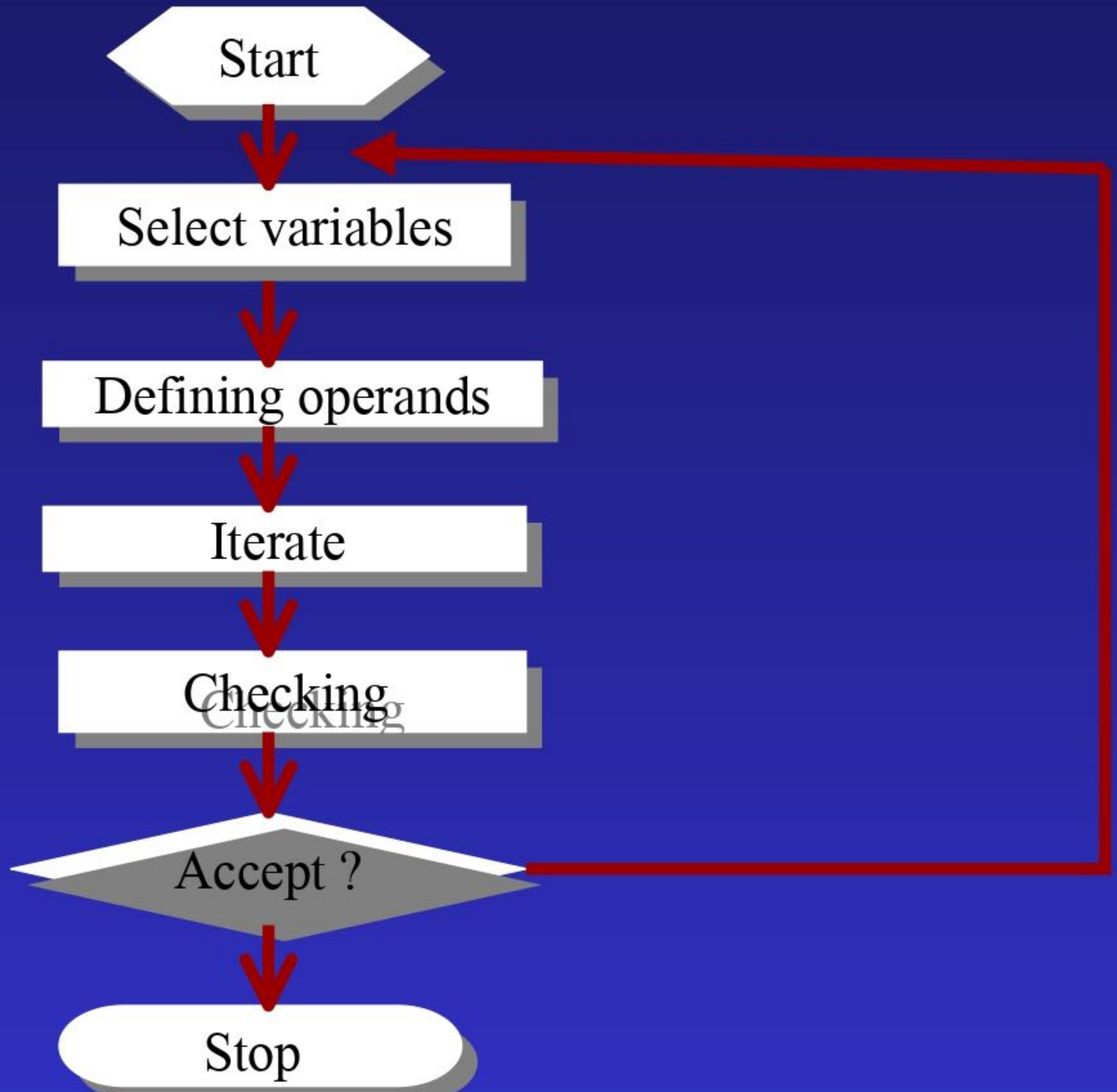
- .We can choose ***through-focus MTF*** or ***through-frequency MTF*** in ***Calculate optical transfer function*** dialog.

- 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.

Surface Data

Gen | Setup | Wavelength | Field Points | Variables | Draw On | Group | Notes

Lens: Triplet 10mm f/2.8 20deg | Zoom 1 of 1 | Efl 10.000000

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	4.249954	V	0.700000		1.800000	K	SK16	C	
2	-31.729657	V	1.199987	V	1.800000	P	AIR		
3	-4.049956	V	0.300000		1.800000		F4	C	
AST	3.859958	V	1.199987	V	1.800000	A	AIR		
5	28.249694	V	0.700000		1.800000		SK16	C	
6	-3.491631	V	8.589907	V	1.800000	K	AIR		
IMS	0.000000		0.000000		3.798090	S			

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.

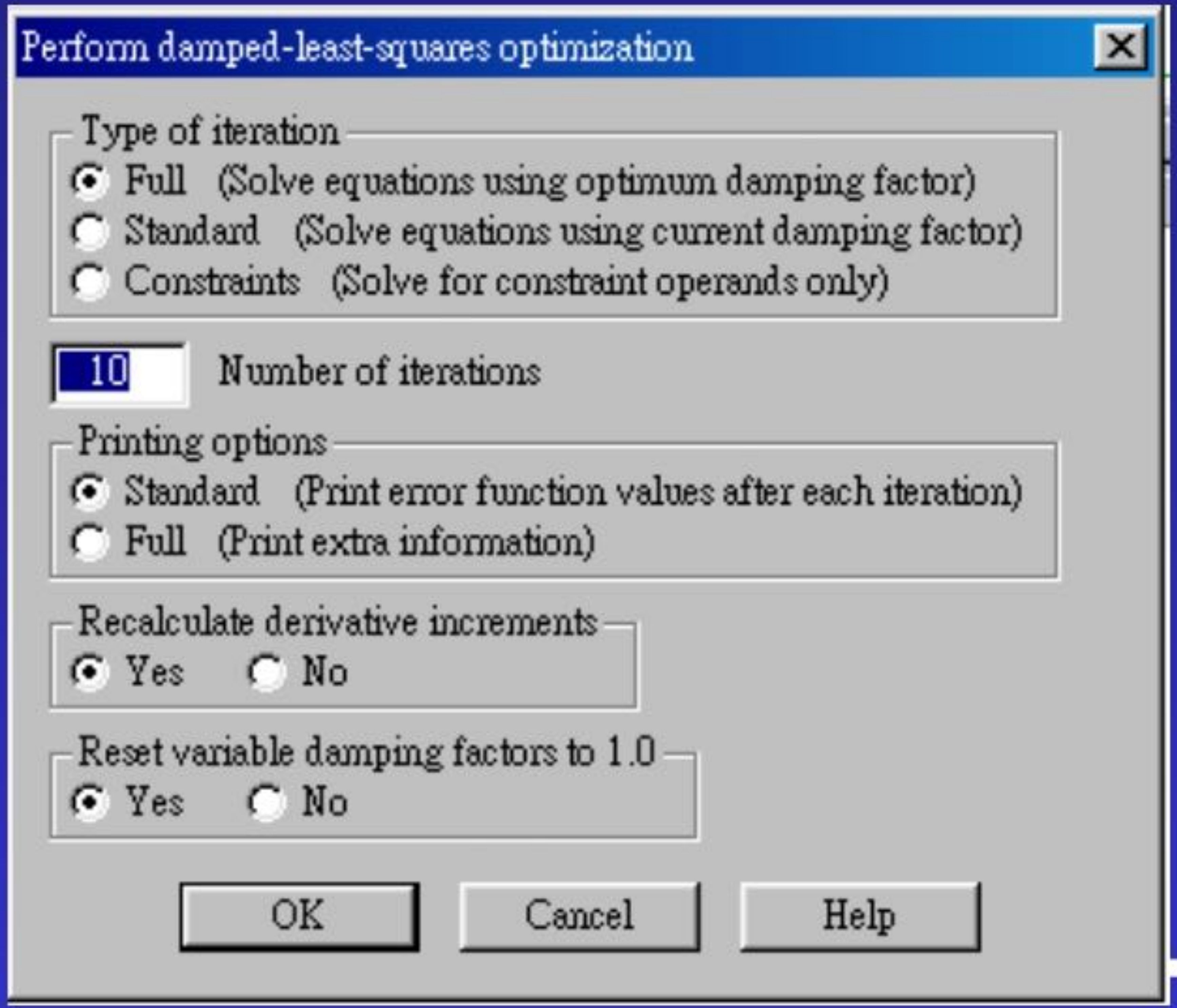
*OPERANDS

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 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

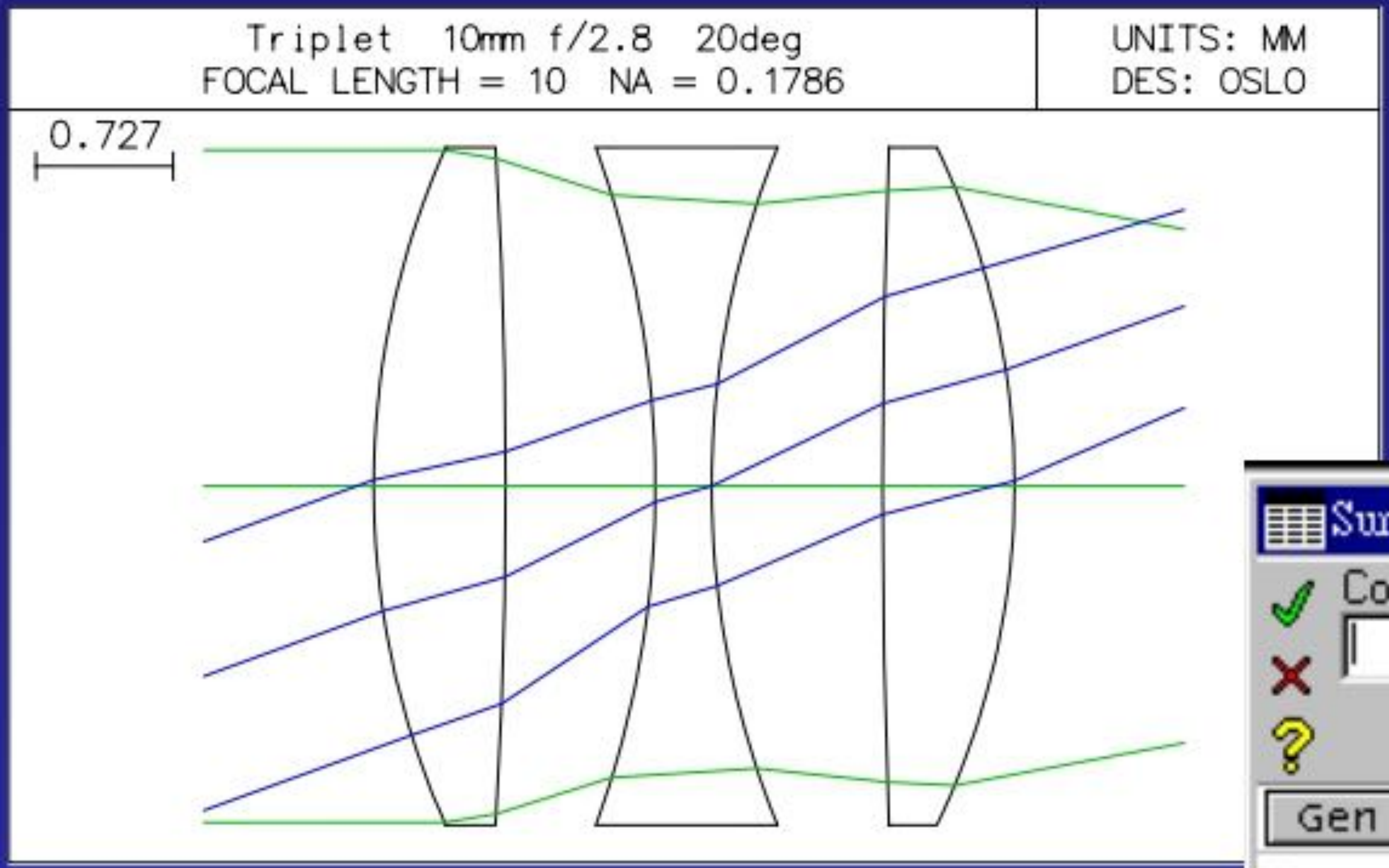
NBR	DAMPING	MIN ERROR	CON ERROR	PERCENT CHG.
0	1.0000e-08	3.821989	--	
1	1.0000e-04	3.380152	--	11.560399
2	1.0000e-04	1.163296	--	65.584503
3	1.0000e-04	0.703656	--	39.511882
4	1.0000e-04	0.663520	--	5.703904
5	1.4380e-05	0.652843	--	1.609209
6	5.4530e-06	0.642279	--	1.618178
7	1.2734e-06	0.638169	--	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

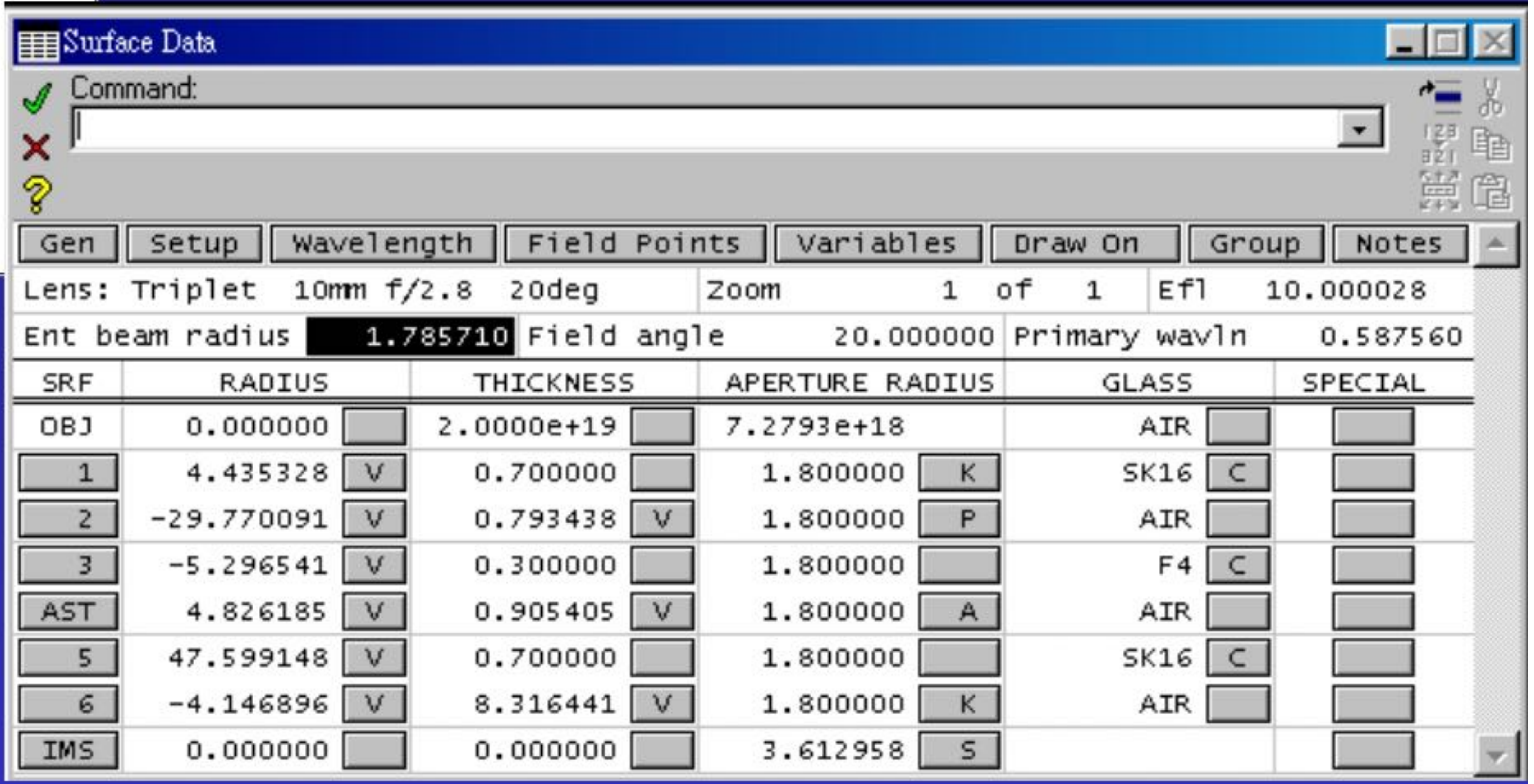
*ITERATE FULL 10

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

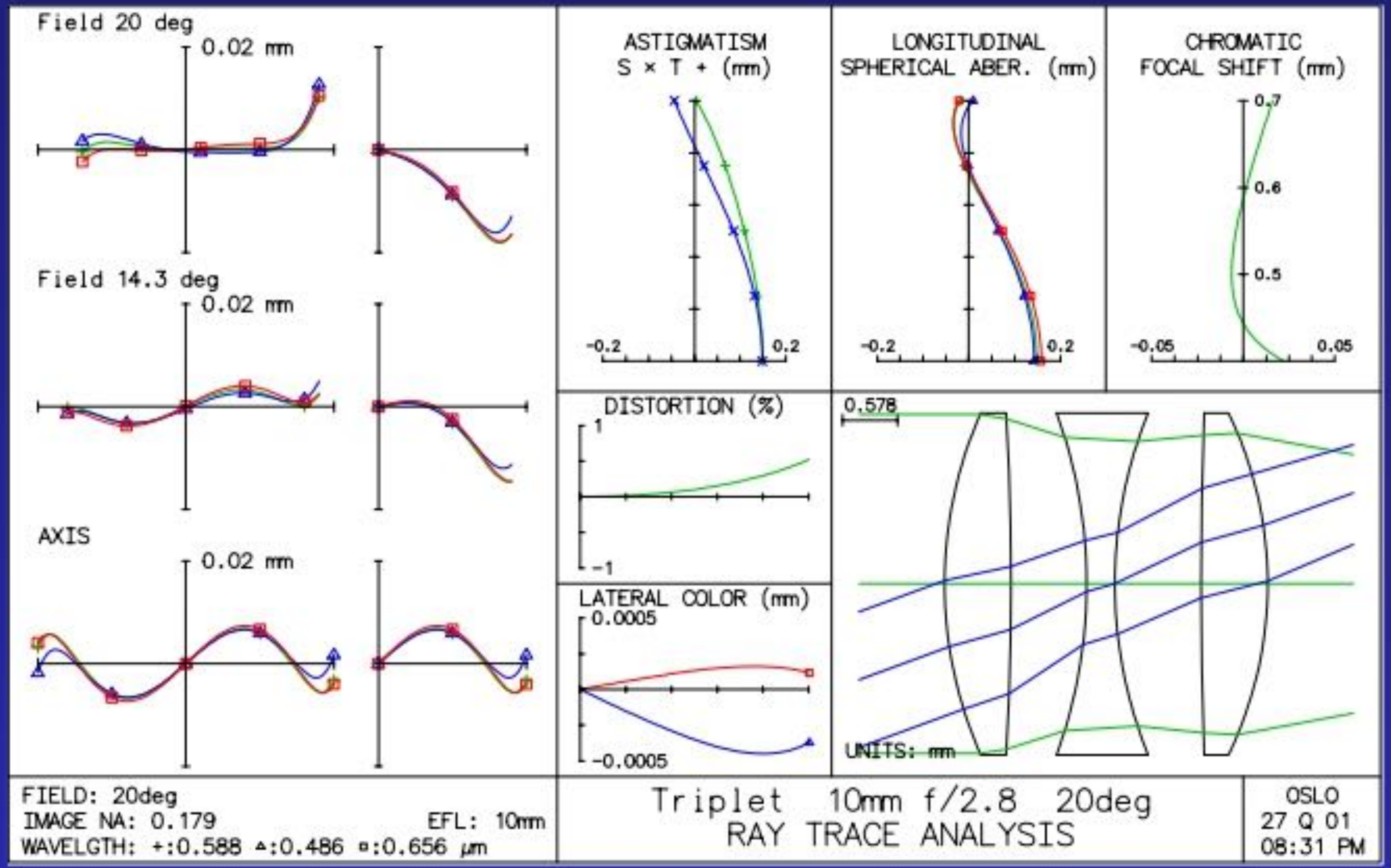




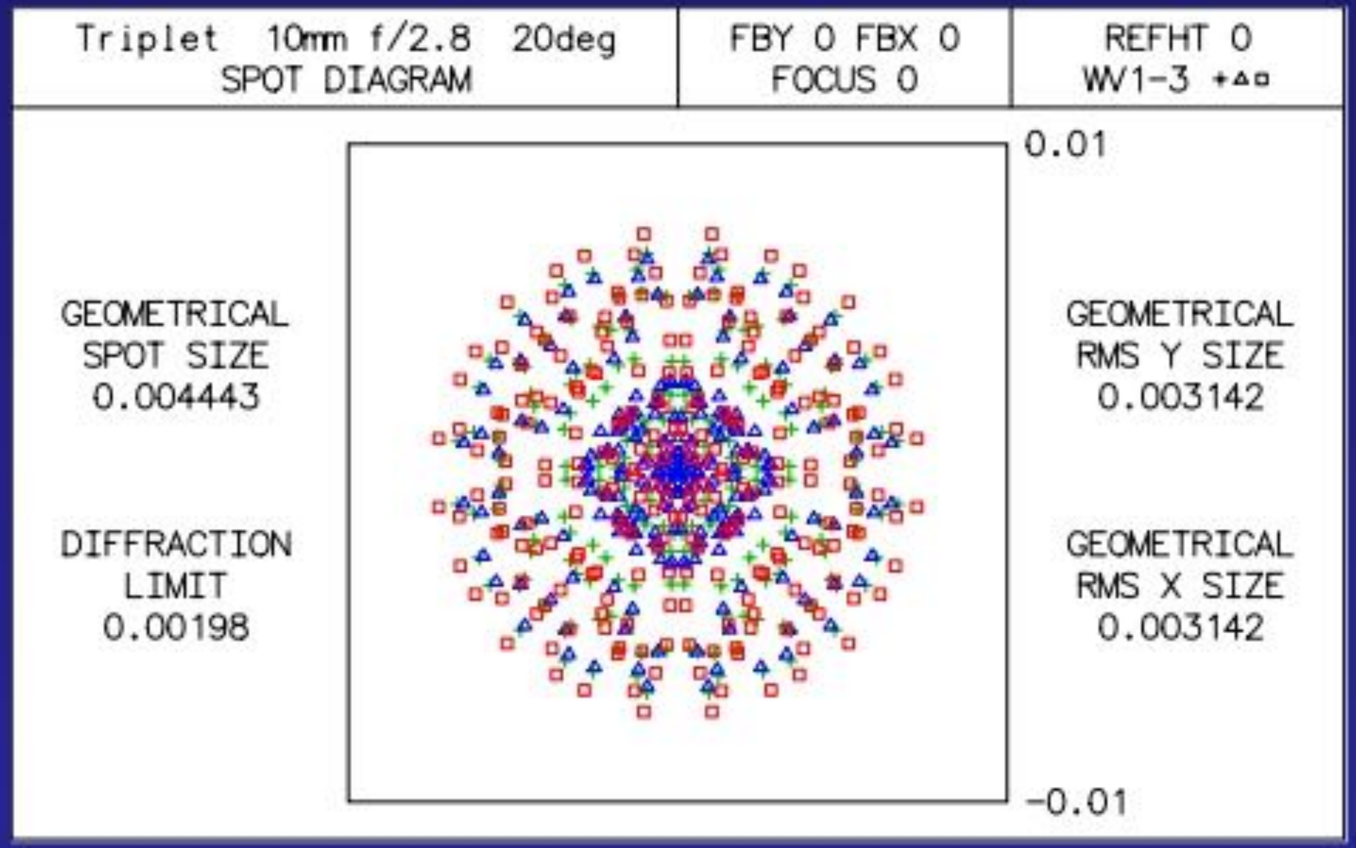
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		2.0000e+19		7.2793e+18		AIR		
1	4.435328	V	0.700000		1.800000	K	SK16	C	
2	-29.770091	V	0.793438	V	1.800000	P	AIR		
3	-5.296541	V	0.300000		1.800000		F4	C	
AST	4.826185	V	0.905405	V	1.800000	A	AIR		
5	47.599148	V	0.700000		1.800000	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

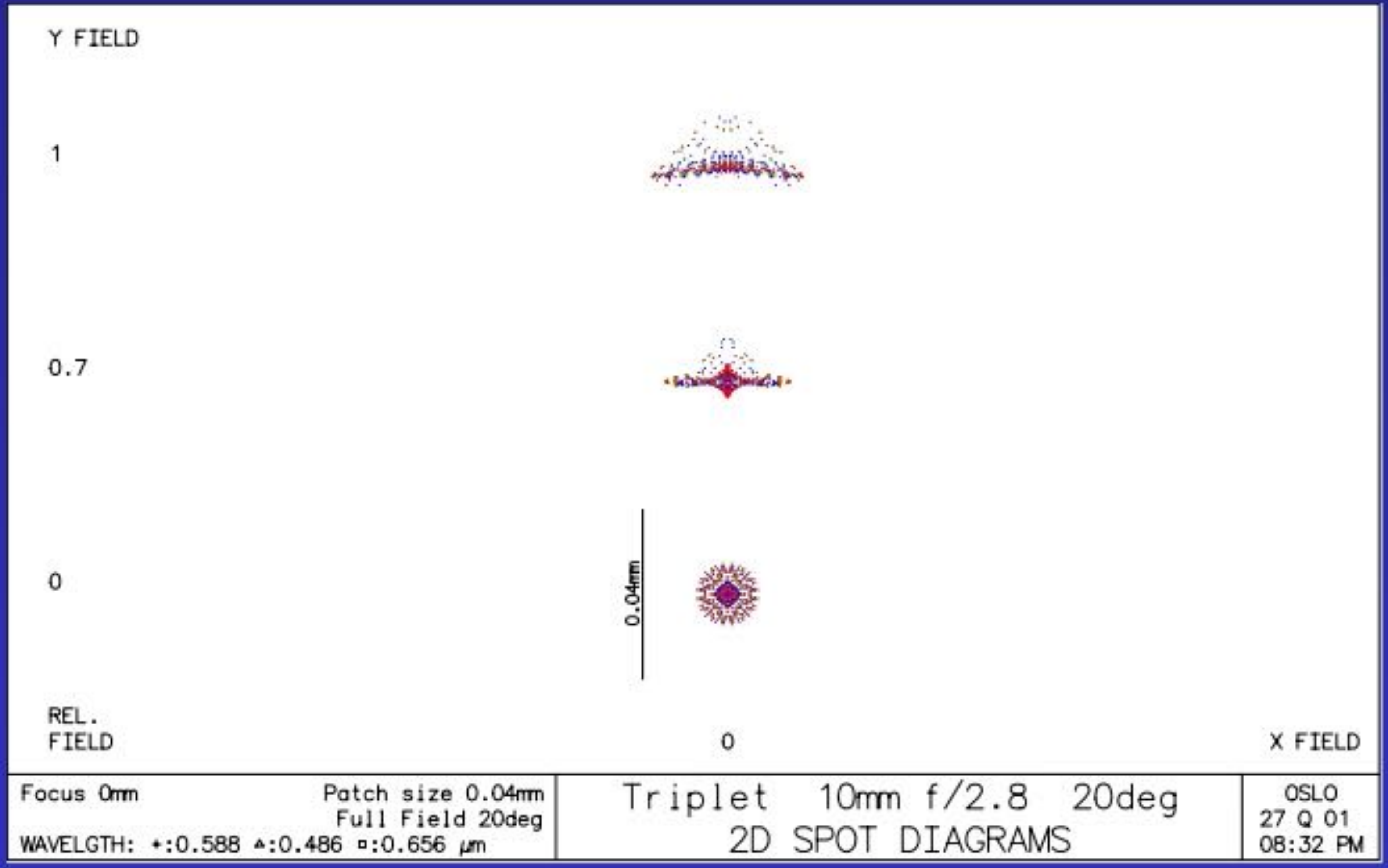
Optimization – curvature radius and thickness

- Checking the image quality
  - Ray analysis report graph



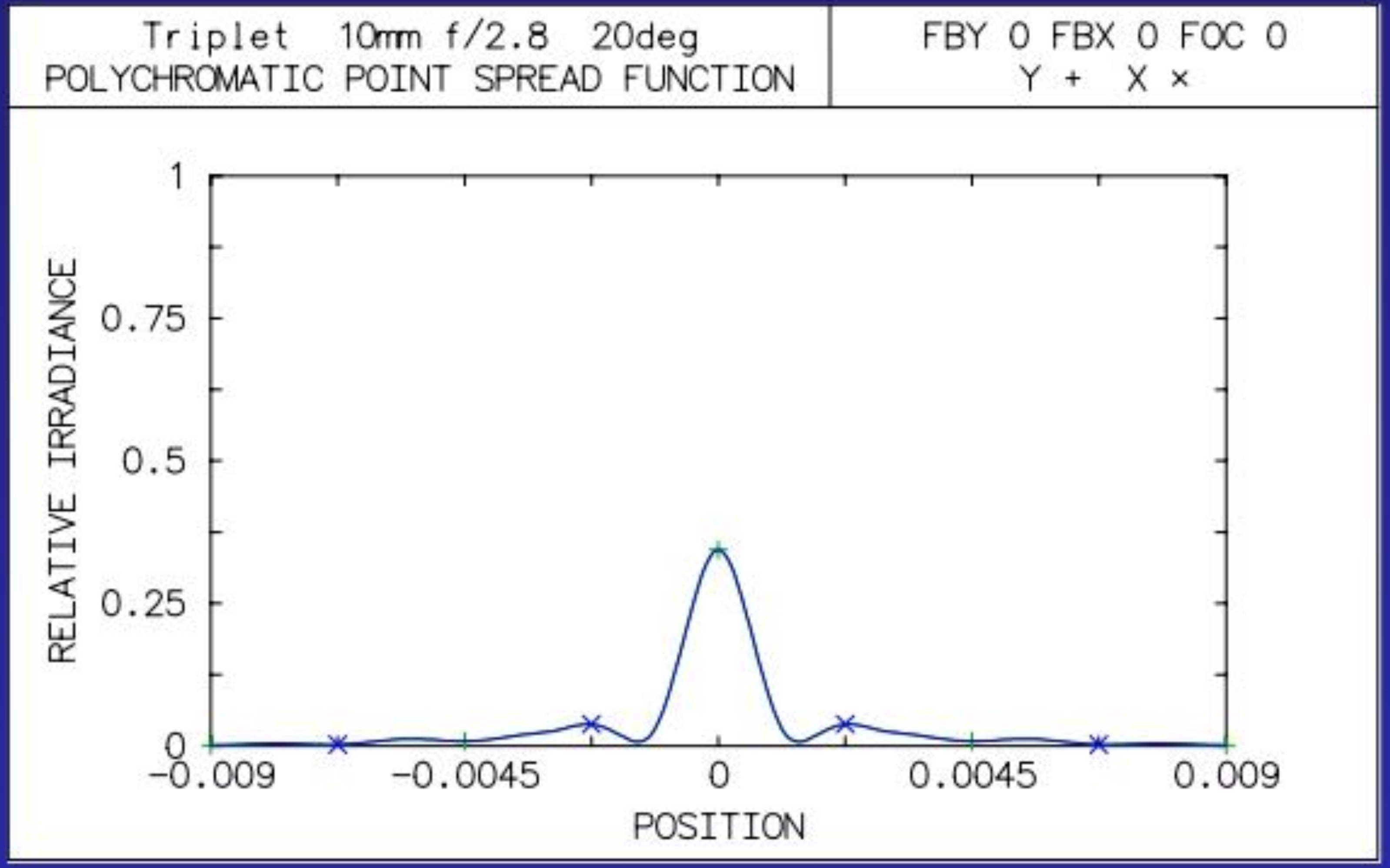
  - Spot diagram report graph



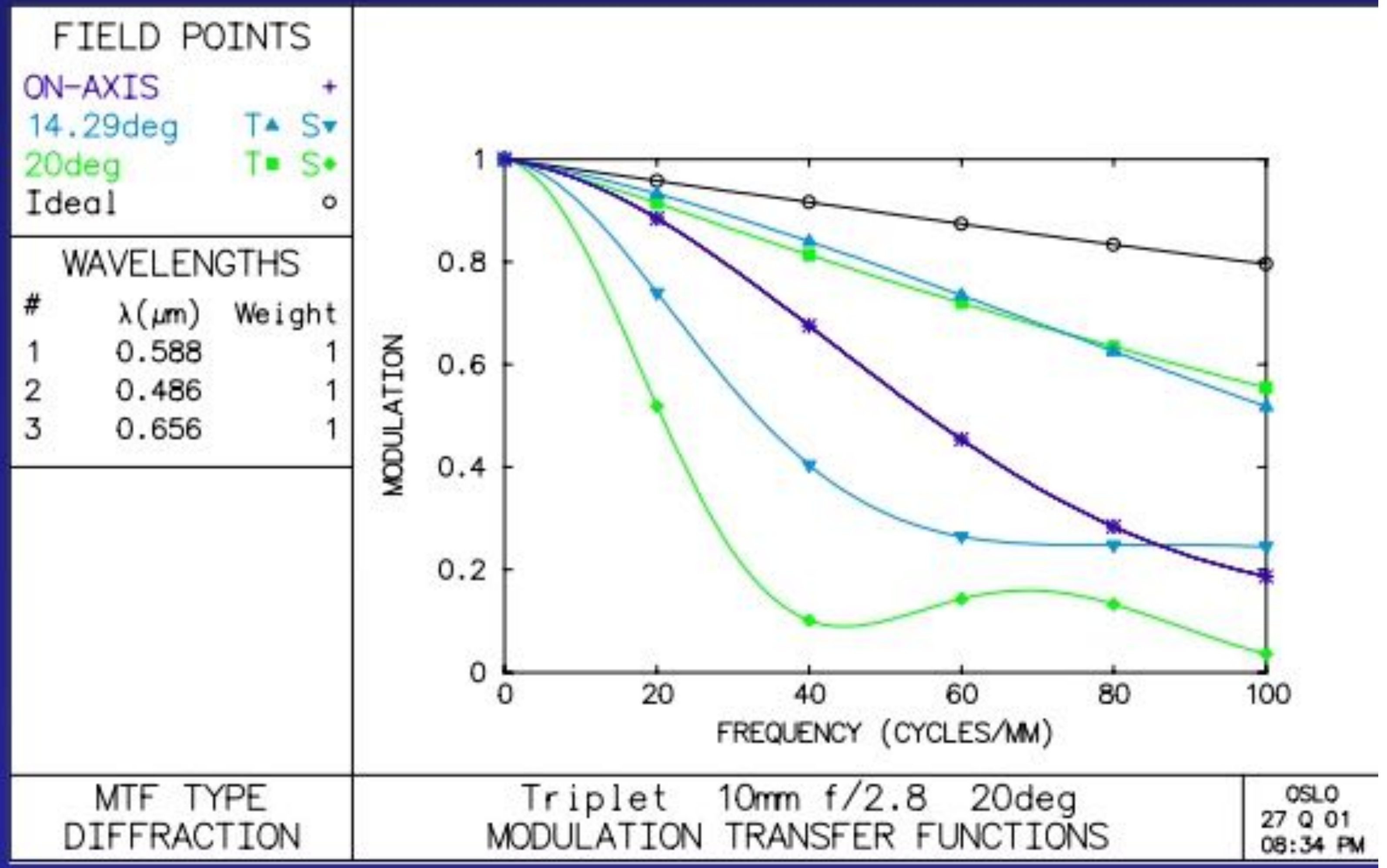


Optimization – curvature radius and thickness

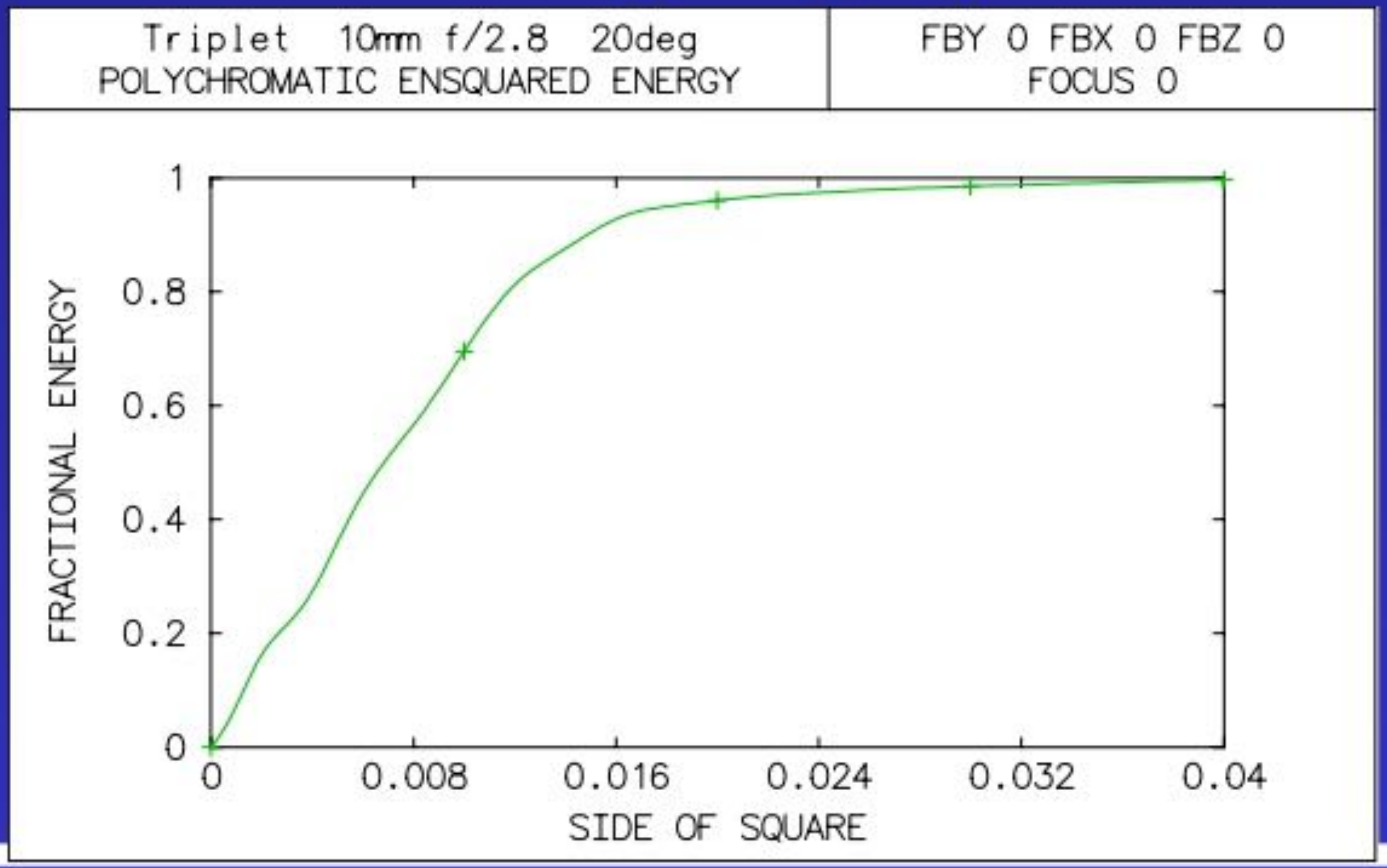
- Step 4 : Checking the image quality
  - PSF report graph



- MTF report graph



- Energy distribution report graph



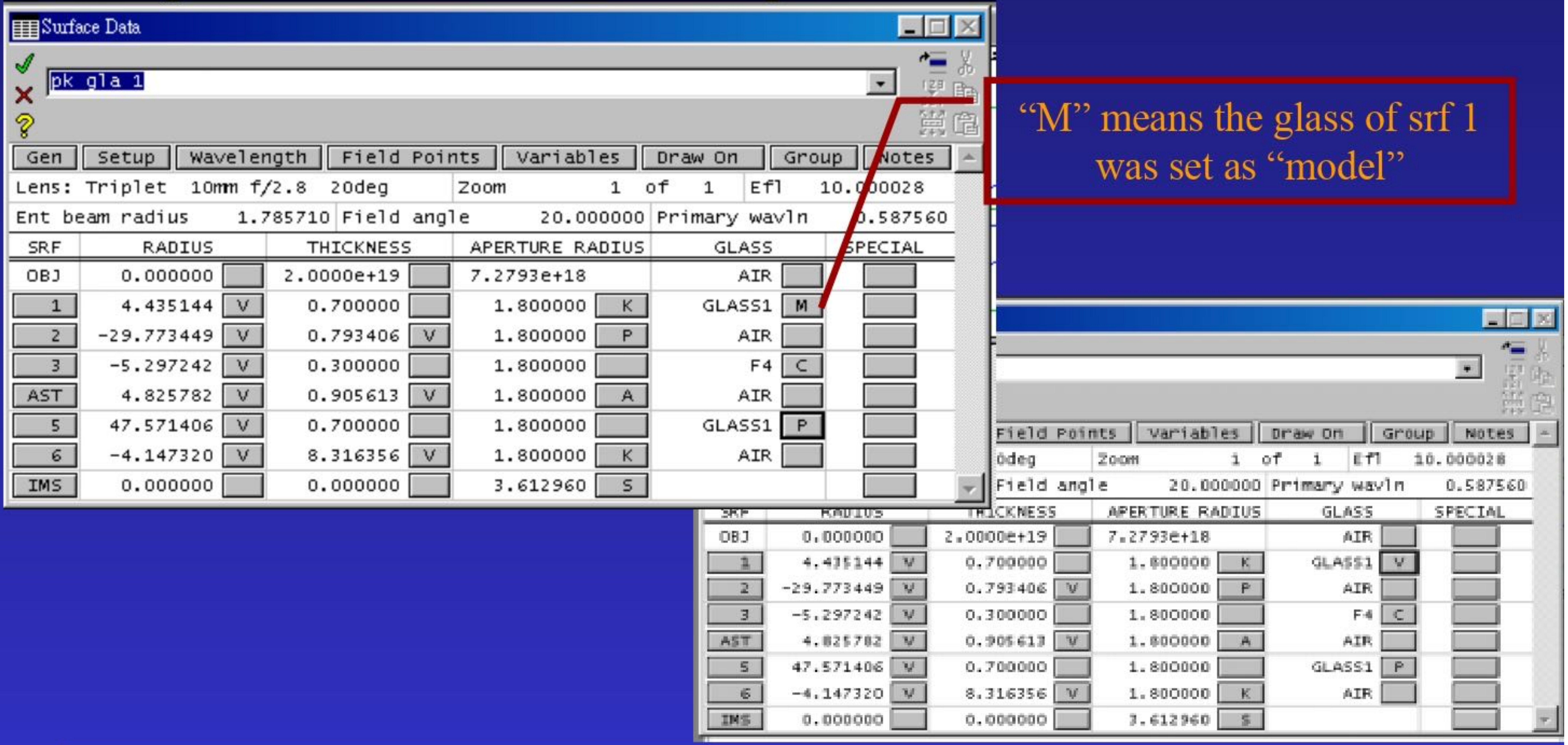
Optimization – materials

- 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.

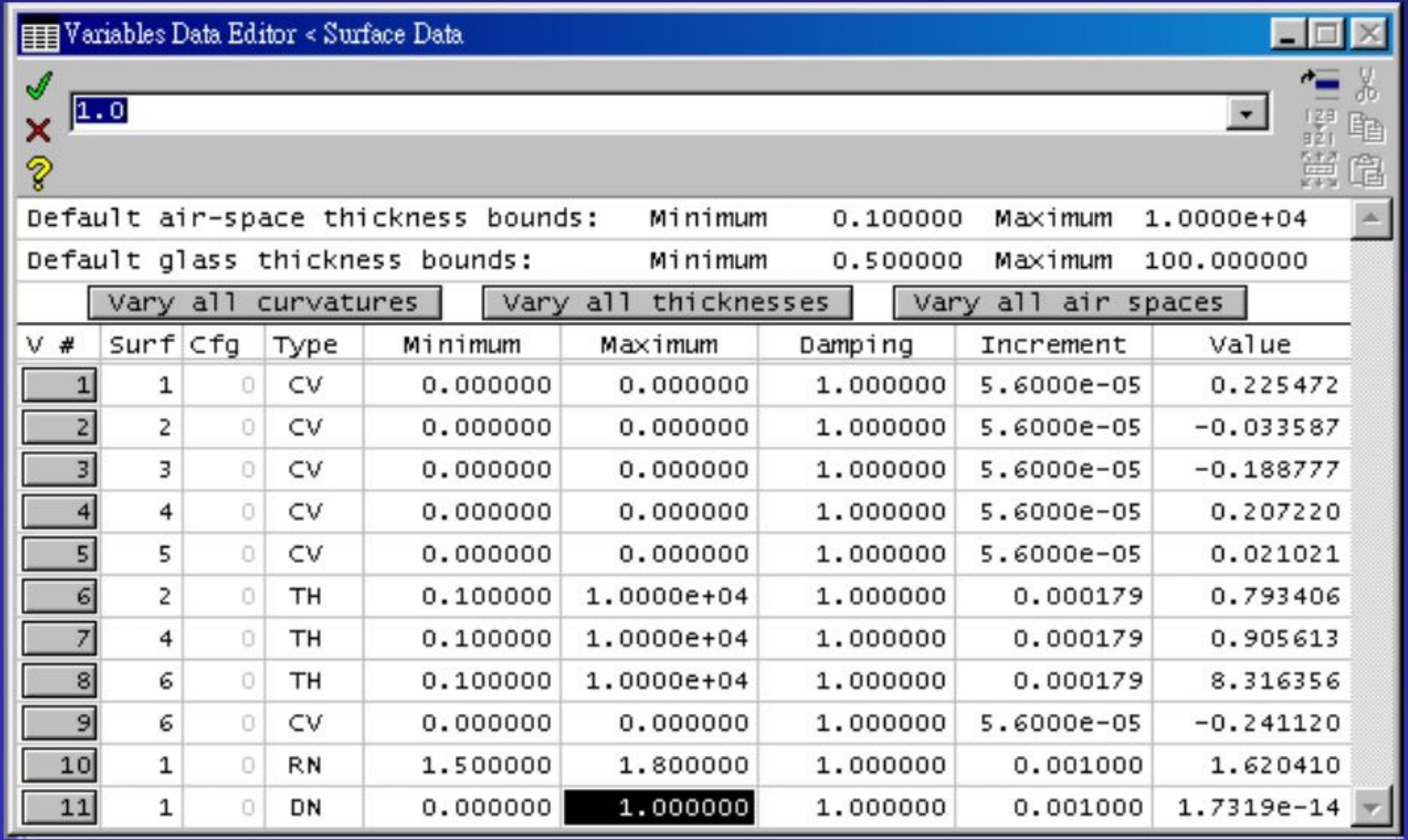
Optimization – materials

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



Optimization – materials

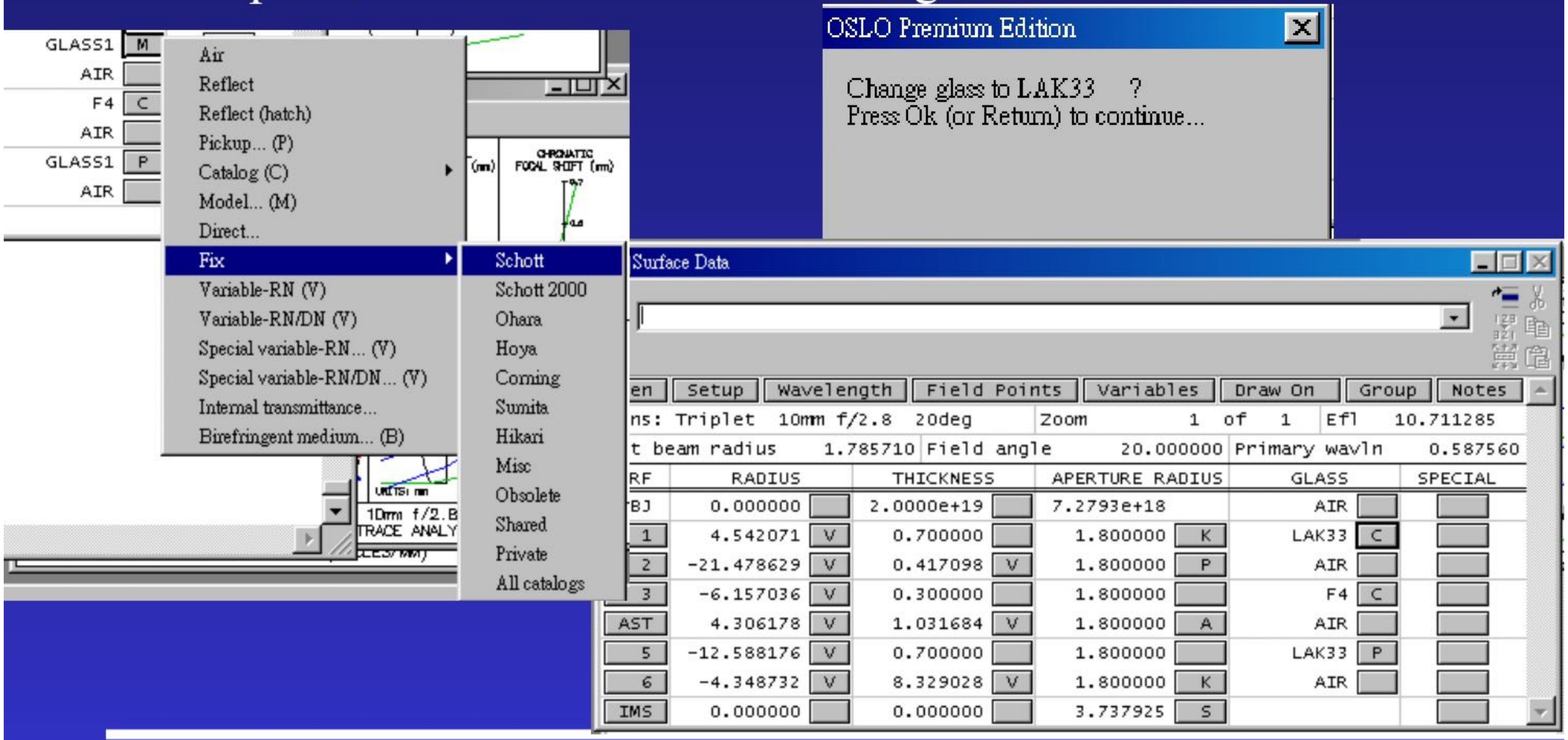
- Setting variables & executing iterate
  - Step 2: define the boundary of variables.
    - Using “Optimize >> Variables ” to define the boundary of RN and DN.



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

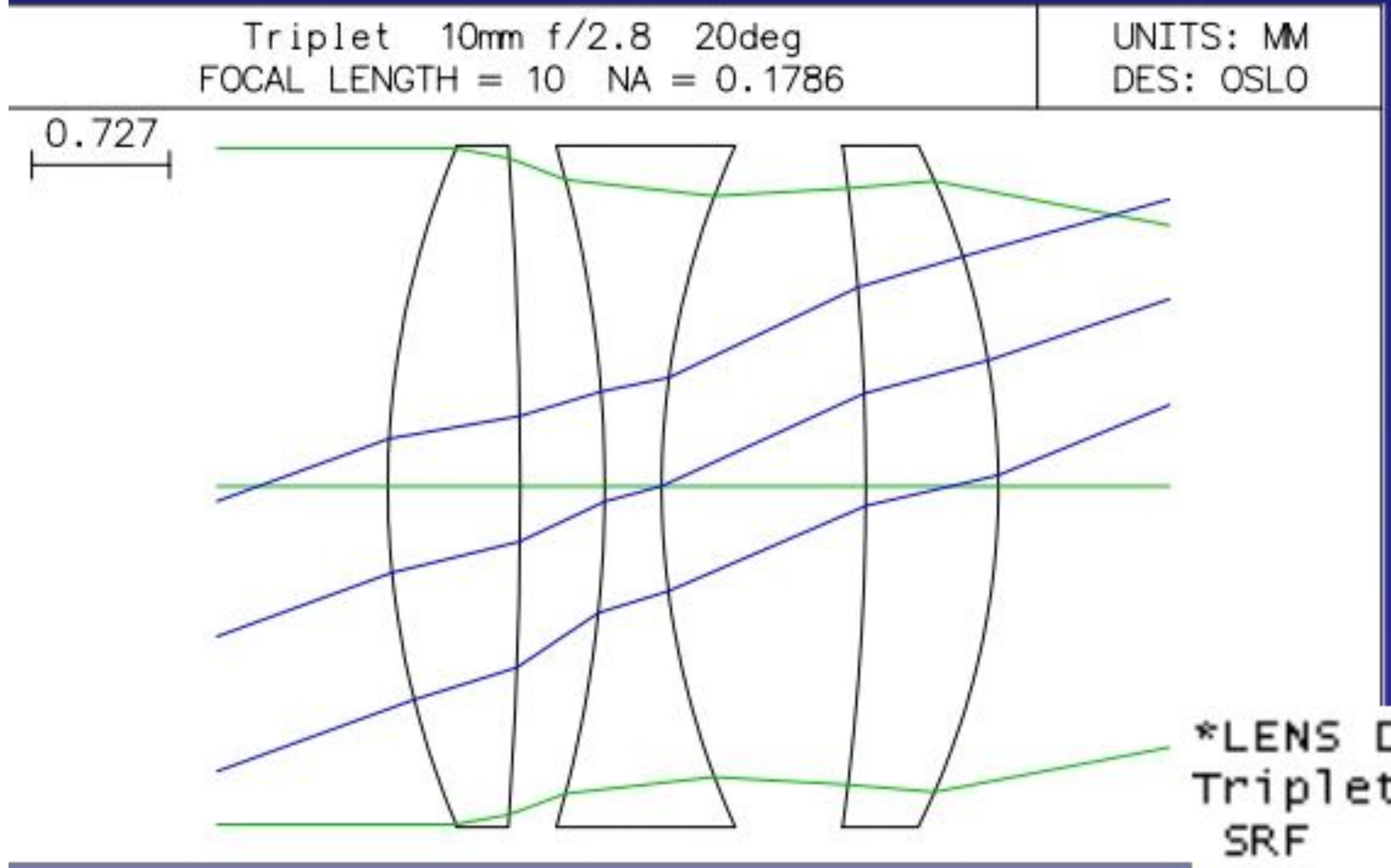
Optimization – materials

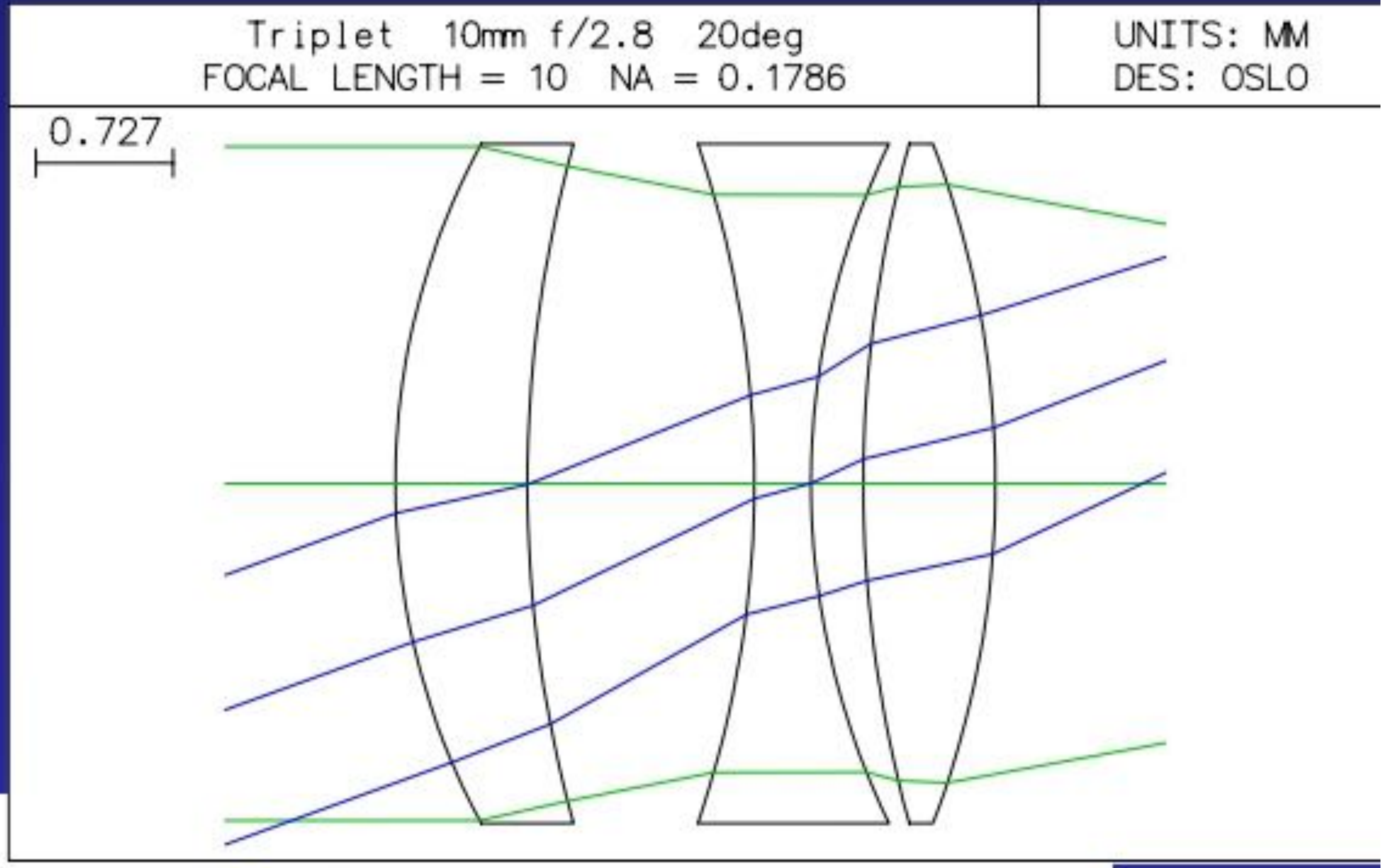
- Setting variables & executing iterate
  - Step 3: execute iterates and fix the glass.



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.



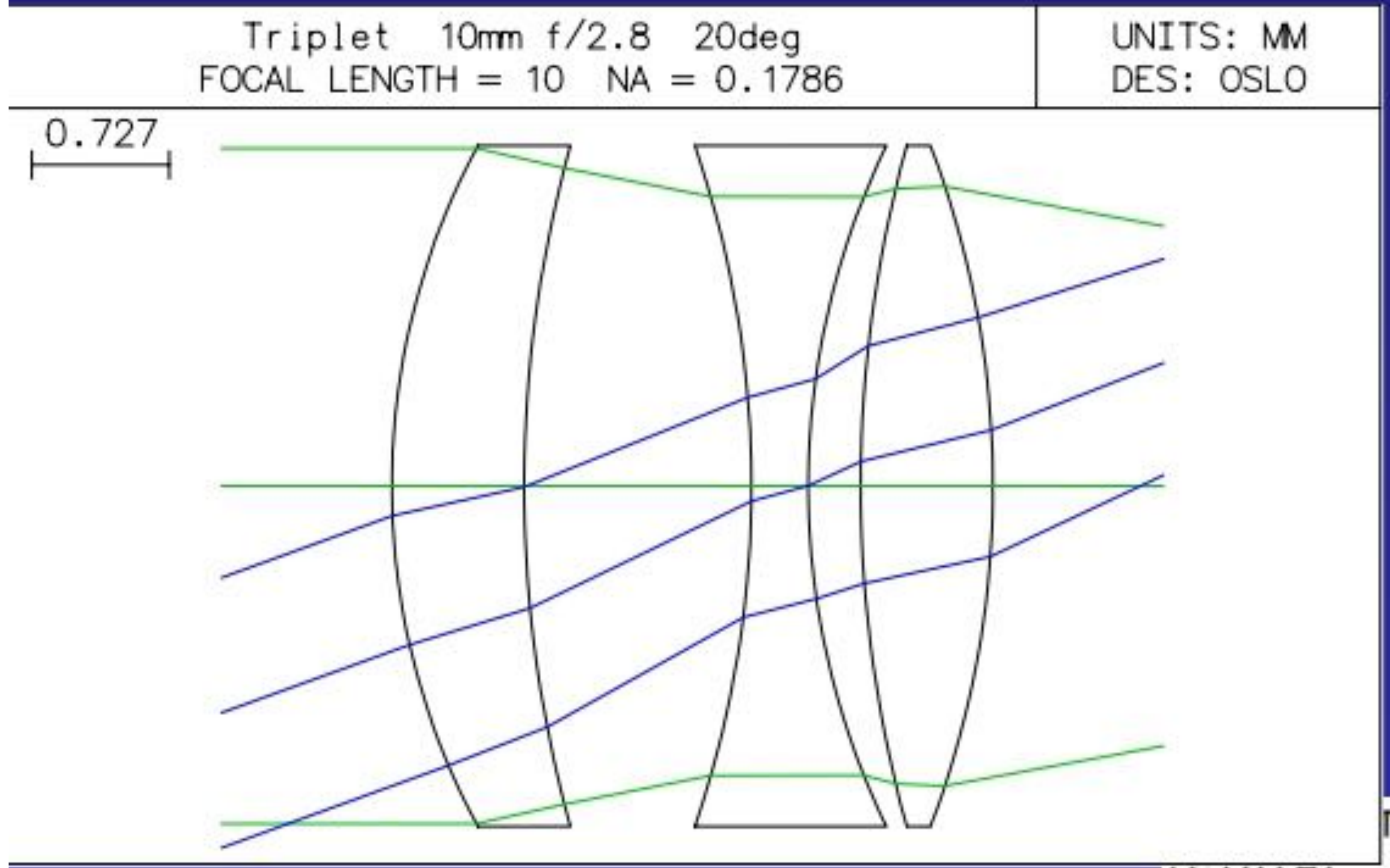


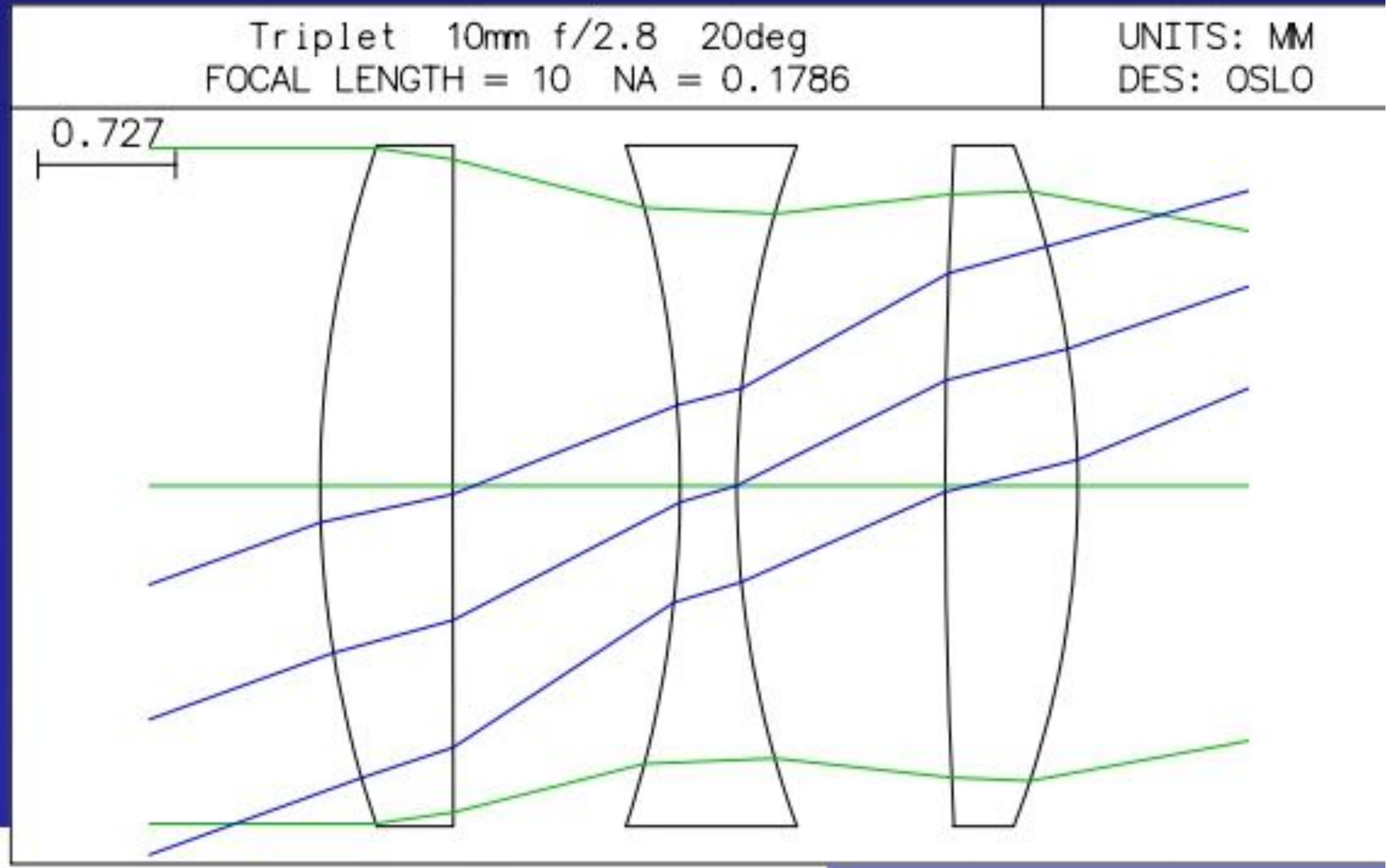
*LENS DATA
Triplet 10mm f/2.8 20deg

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.



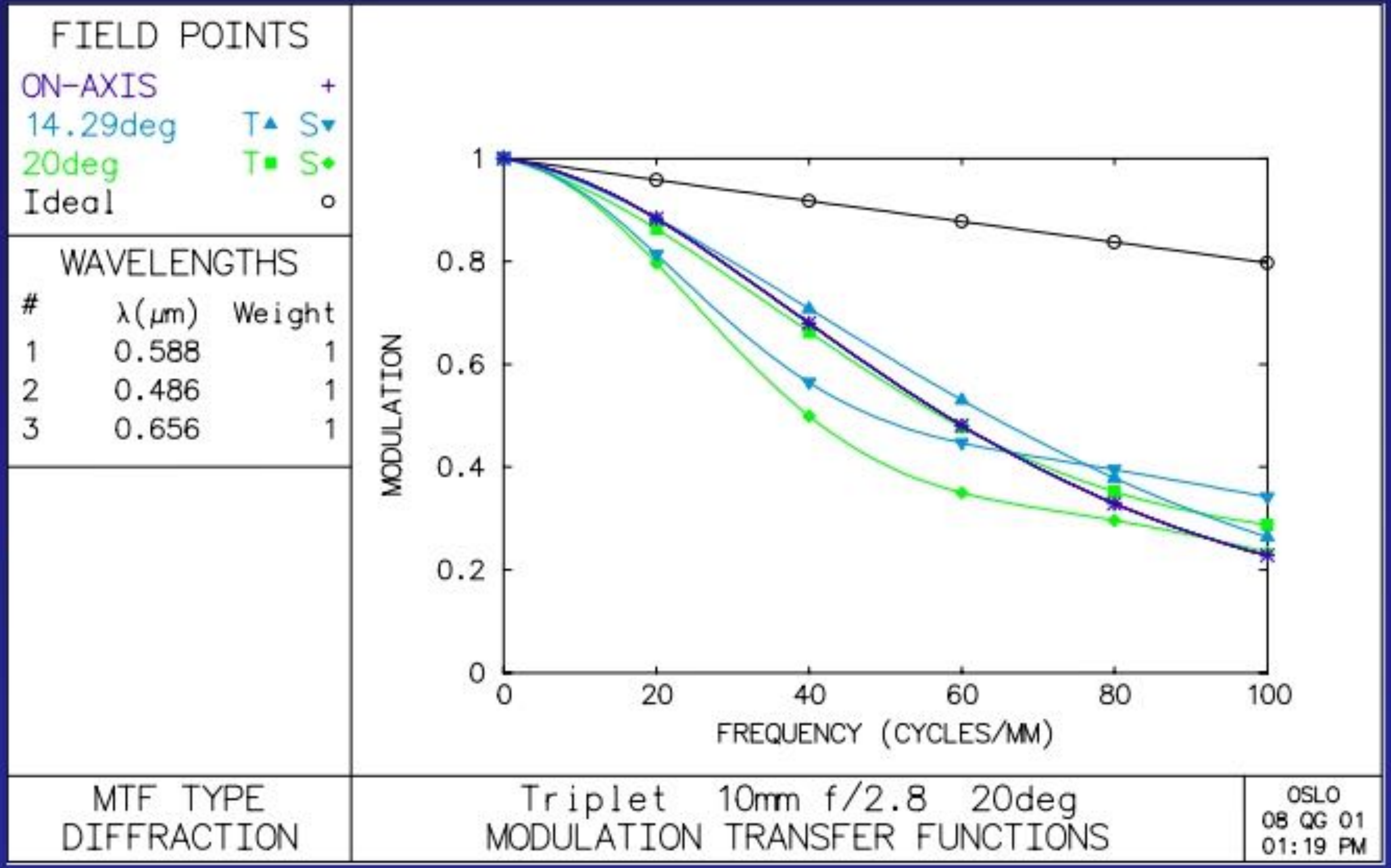


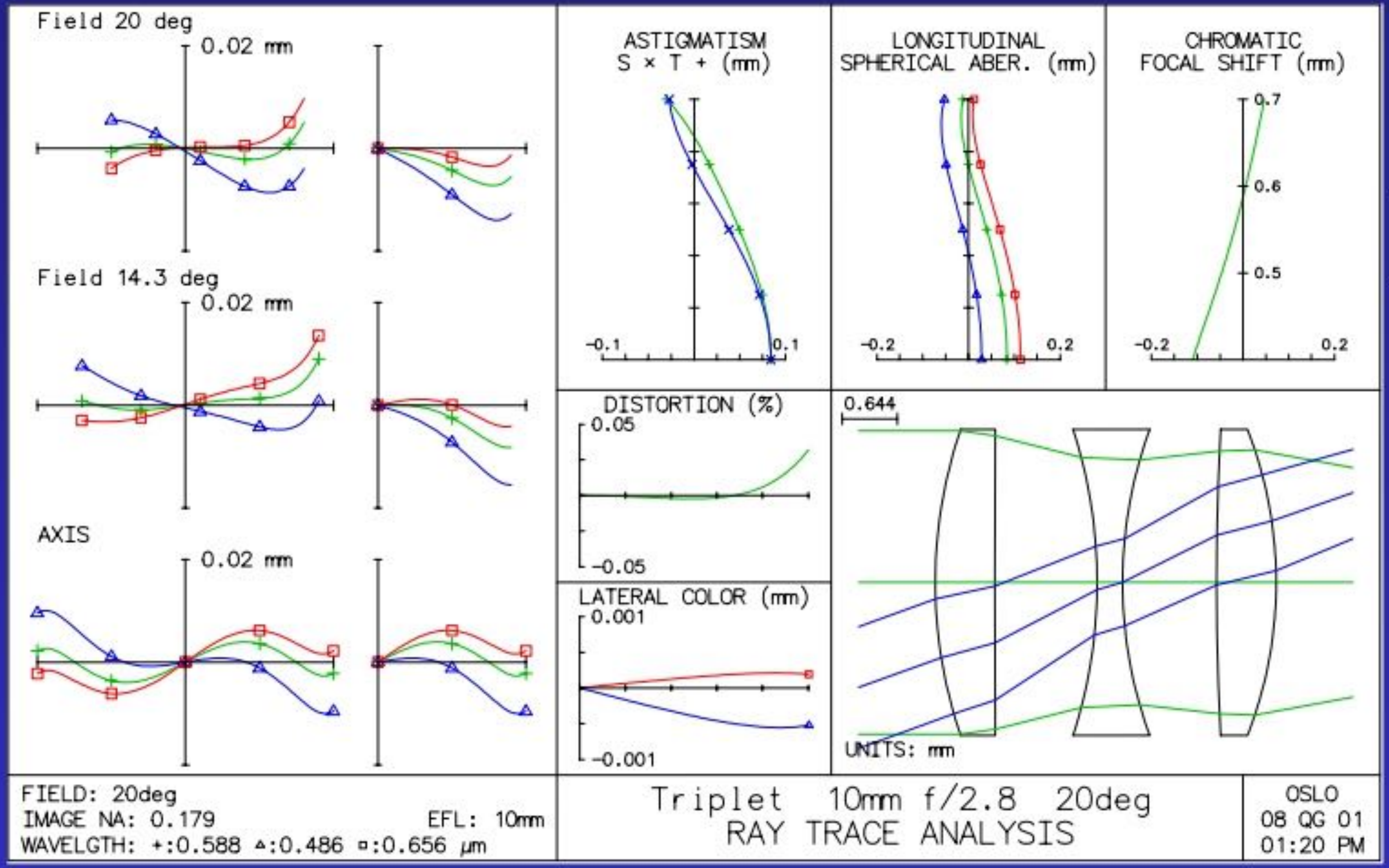
TA
iplet 10mm f/2.8 20deg

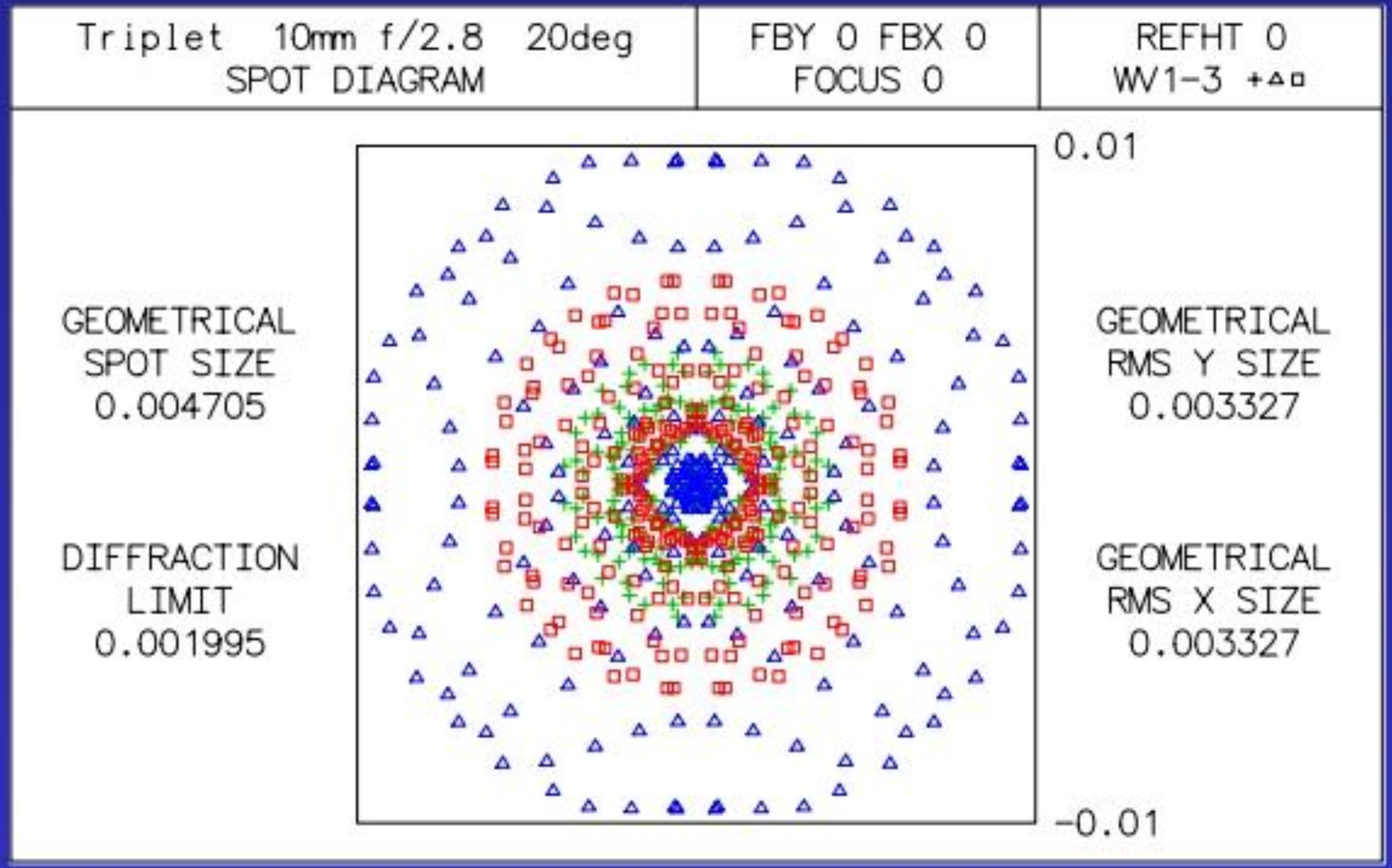
SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	2.0000e+19	7.2793e+18	AIR		
1	3.799887 V	0.700000	1.800000 K	LAK33	C	
2	6.786396 V	1.200000	1.800000 P	AIR		
3	-5.567235 V	0.300000	1.800000	F6	C	
AST	4.141357 V	0.275827 V	1.800000 A	AIR		
5	6.737831 V	0.700000	1.800000	LAK33	P	
6	-5.080154 S	8.368923 V	1.800000 K	AIR		
IMS	--	--	3.615703 S			

Optimization – the image quality after re-optimize

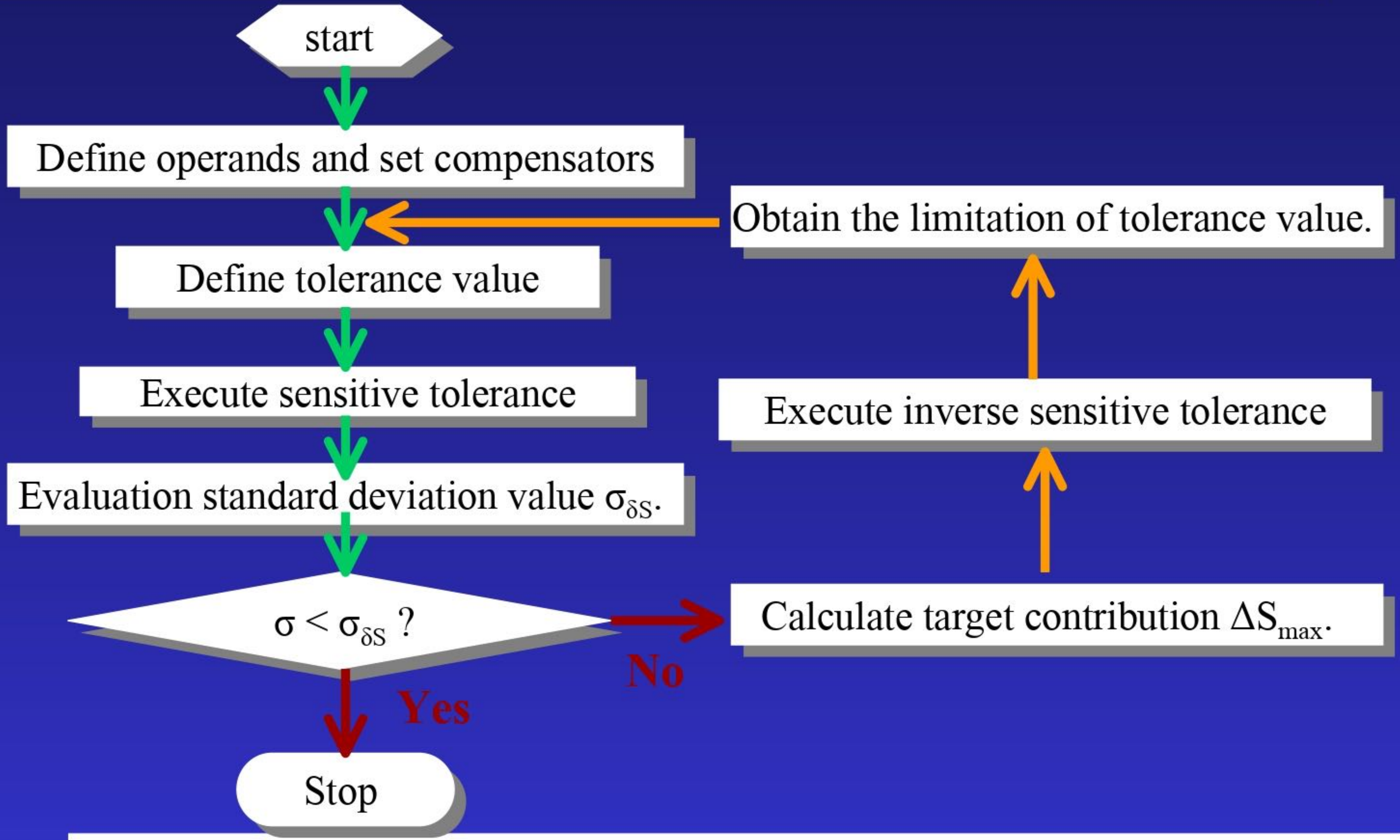
- Checking
  - Checking the image equality







Tolerance analysis



Tolerance analysis

- Sensitive tolerance
  - The change in system performance S from nominal performance S_0

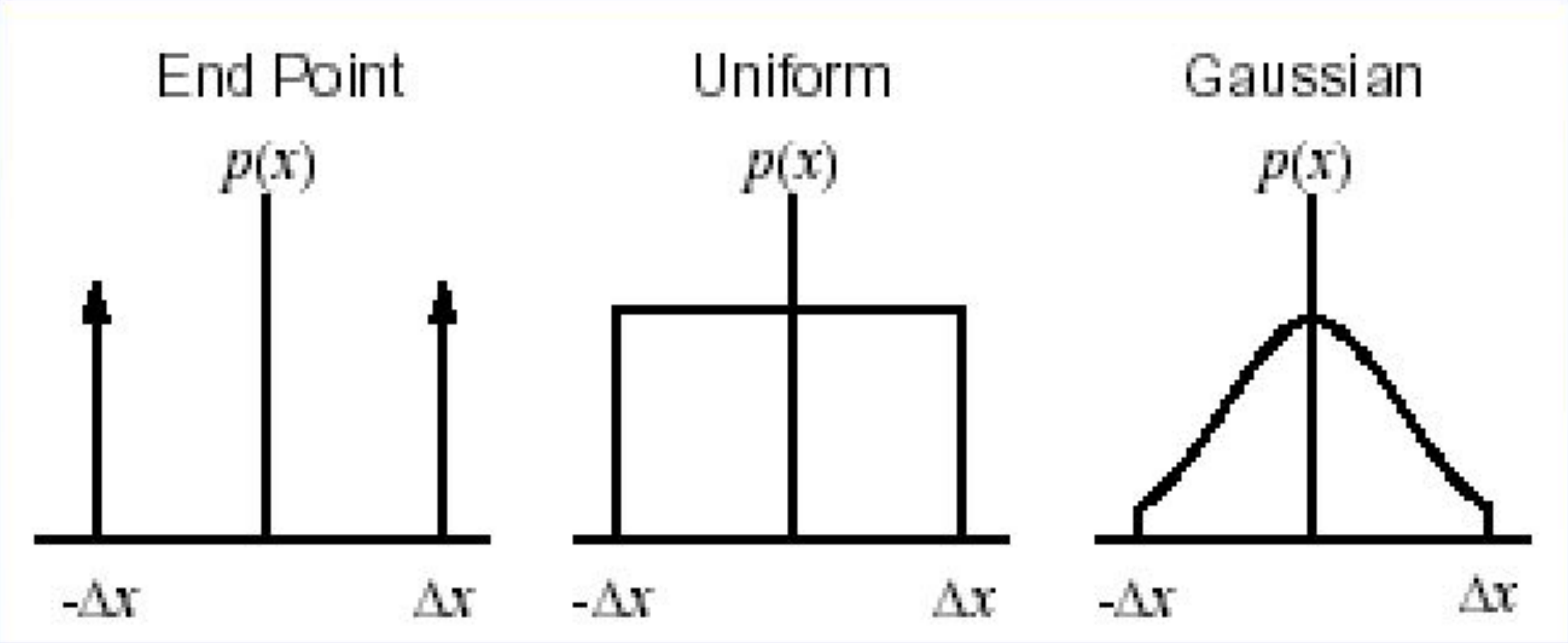
$$\delta S = S - S_0$$

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

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

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

Distribution	K
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 δS_{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.

*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

  - 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.

*OPERANDS

	OP	MODE	WGT	NAME	VALUE	%CNTRB	DEFINITION
O	8	M	0.250000	Yrms1	0.001859	4.57	RMS
O	23	M	0.500000	Xrms2	0.003978	41.88	RMS
O	38	M	0.500000	Yrms2	0.002314	14.18	RMS
O	53	M	0.125000	Xrms3	0.003153	6.58	RMS
O	68	M	0.125000	Yrms3	0.007039	32.79	RMS

MIN RMS ERROR: 0.003549

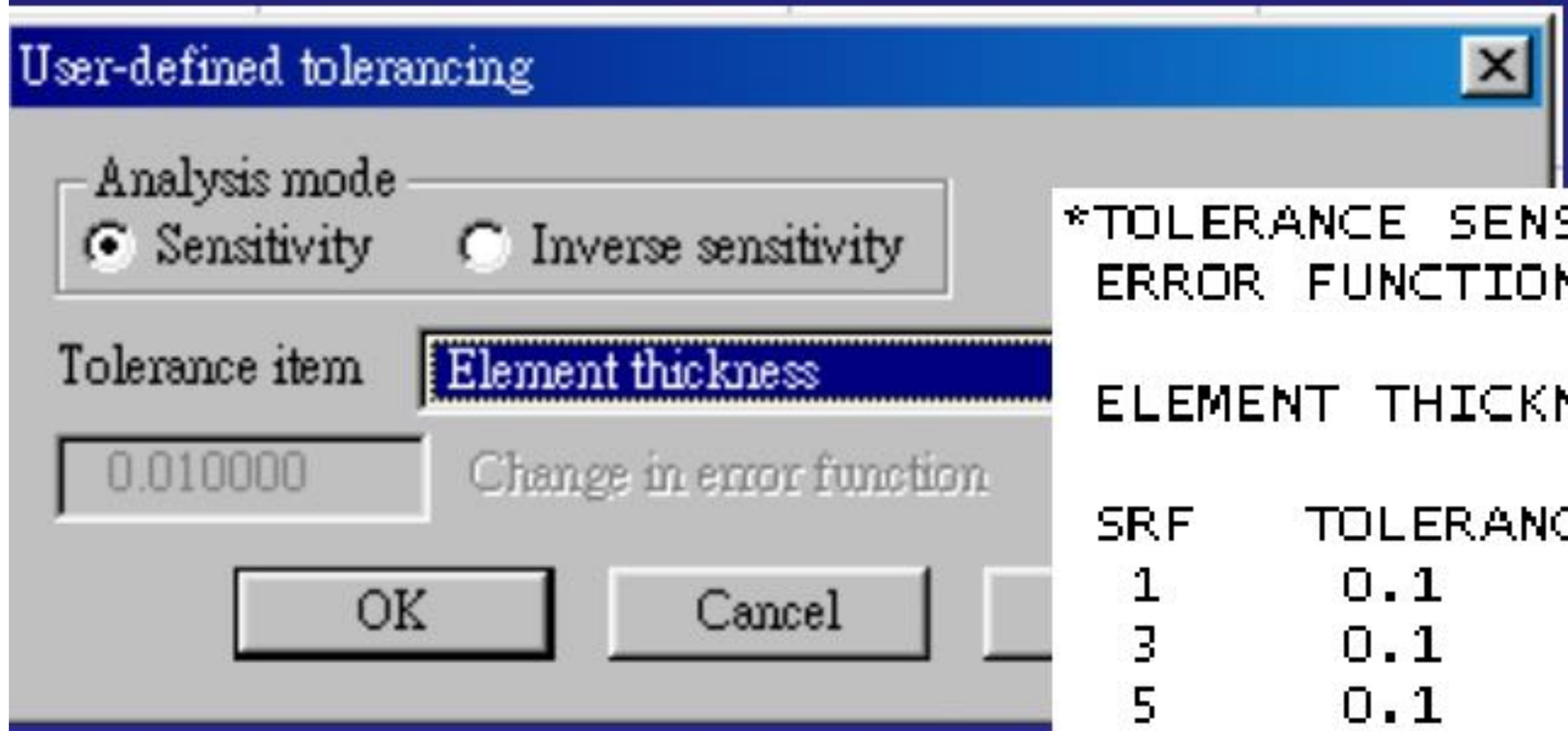
Tolerance – element thickness

- 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
      RADIUS   RD TOL     FRINGES THICKNESS TH TOL              RN TOL   DECEN   TILT
 SRF CON CNST CC TOL     PWR    IRR   TLC TOL DZ TOL      GLASS   V TOL   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 Toleranceing”, choose the “sensitive” mode and select the tolerance item you desired.
  - We will do the “element thickness ” tolerance first.



Nominal value

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

 ELEMENT THICKNESS TOLERANCE
                     ERROR FUNCTION CHANGE          COMPENSATED CHANGE
 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
```

Tolerance – element thickness

- Step 4 : Evaluation
  - Let the maximum allowed spot size is 18 µm. Since the nominal value of spot size is 3.55 µm, the maximum allowed change is 14.45 µm (δS_{max}).
  - If we desire the probability success rate to be 99%, then the desired standard deviation is 5.78 µm (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		COMPENSATED 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

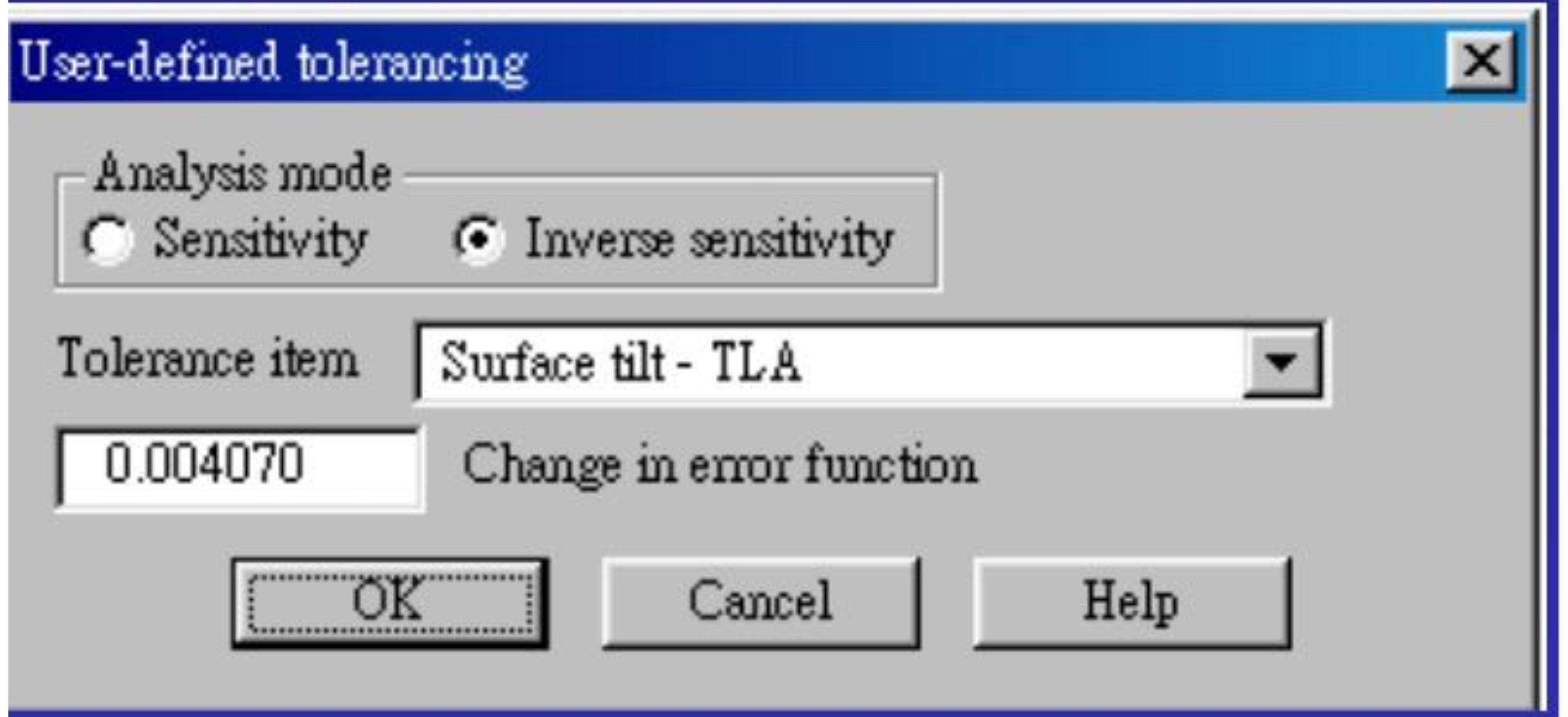
	UNCOMPENSATED	COMPENSATED
WORST CASE CHANGE	0.089281	0.084477
STANDARD DEVIATION		
RSS	0.036778	0.034877
UNIFORM	0.021234	0.020136
GAUSSIAN	0.016175	0.015339

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	.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		COMPENSATED CHANGE	
SRF	TOLERANCE	PLUS PERT	MINUS PERT	PLUS PERT	MINUS PERT
1	0.2	0.005553	0.004928	0.004891	0.003318
2	0.25	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	[illegible]	[illegible]
UNIFORM	0.008052	0.007721
GAUSSIAN	[illegible]	[illegible]

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	[illegible]	[illegible]
UNIFORM	0.006918	0.006589
GAUSSIAN	[illegible]	0.005615

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)

		ERROR FUNCTION CHANGE		COMPENSATED CHANGE	
SRF	TOLERANCE	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

	UNCOMPENSATED	COMPENSATED
WORST CASE CHANGE	0.022608	0.021790
STANDARD DEVIATION		
RSS	[illegible]	[illegible]
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