

Introductory exercise for OSLO

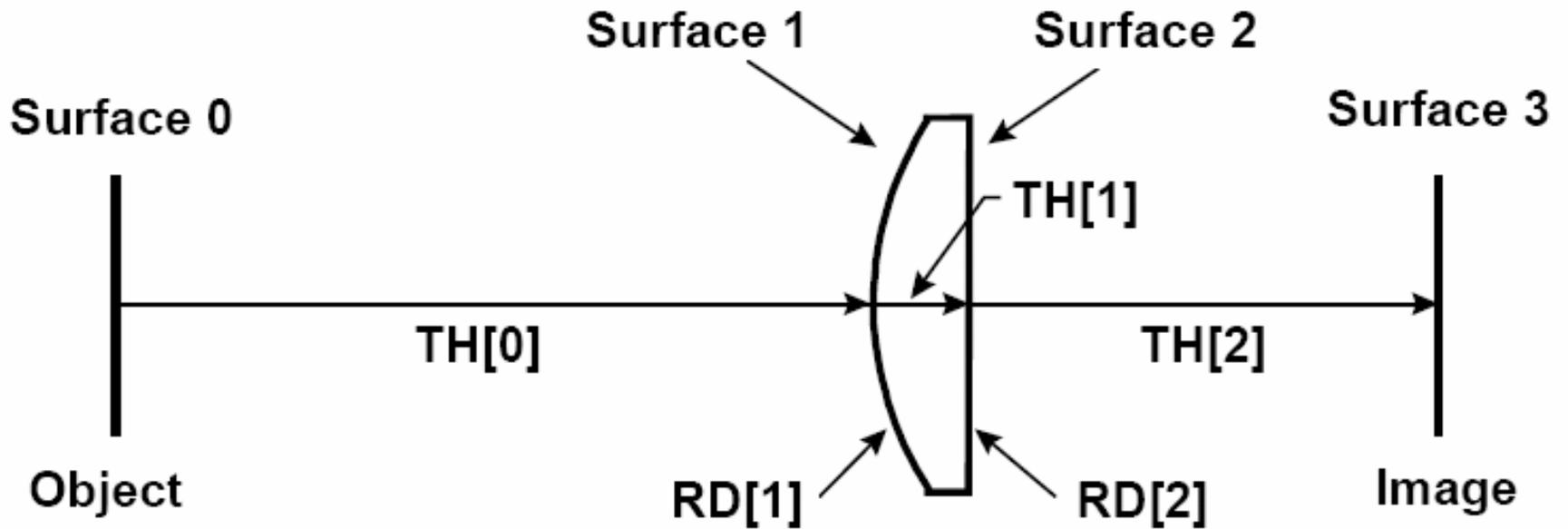


A typical configuration of OSLO

The screenshot shows the OSLO Premium Edition interface. The main window is divided into several sections:

- Spreadsheet:** A table showing lens parameters for 'Landscape 1'. The table has columns for SURF, RADIUS, THICKNESS, APERTURE RADIUS, GLASS, and SPECIAL. The current surface is 'S01'.
- Main Window:** The central area containing various analysis windows:
 - UVW 1 - Ray Intercept Curves Analysis:** Displays ray intercept curves for different wavelengths.
 - UVW 2 - Wavefront Analysis:** Shows wavefront plots for different wavelengths, including color-coded maps and 3D surface plots.
 - UVW 3:** Shows a ray diagram with a lens and rays.
- Status Bar:** Located at the bottom left, showing 'Test on: On', 'Page: node: 01', and 'Graphics: auto: On'.
- Text Window:** A window showing iteration results for 'ITERATE FULL' with columns for MFR, DAMPING, MIN ERROR, CON. ERROR, and PERCENT CHG.
- Slider-wheel Window:** A window with sliders for 'DV 2' and 'DV 4', both set to 0.000000, with a 'Step: 0.001'.

Surface numbering



Sign conventions

Sign conventions for centered systems

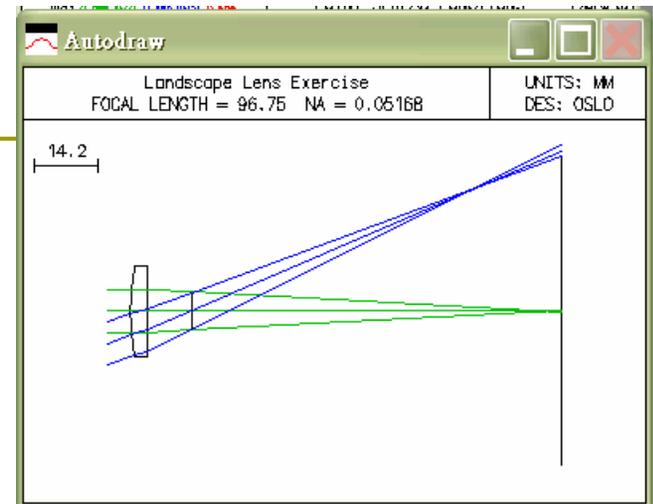
RADIUS OF CURVATURE	The radius of curvature, or curvature of a surface is positive if the center of curvature lies to the right of the surface.
THICKNESS	The thickness separating two surfaces is positive if the next surface lies to the right of the current surface; otherwise it is negative.
REFRACTIVE INDEX	OSLO expects all refractive indices to be provided with positive signs. Reflecting surfaces are specified explicitly by the designation, rfl .

Steps in the exercise

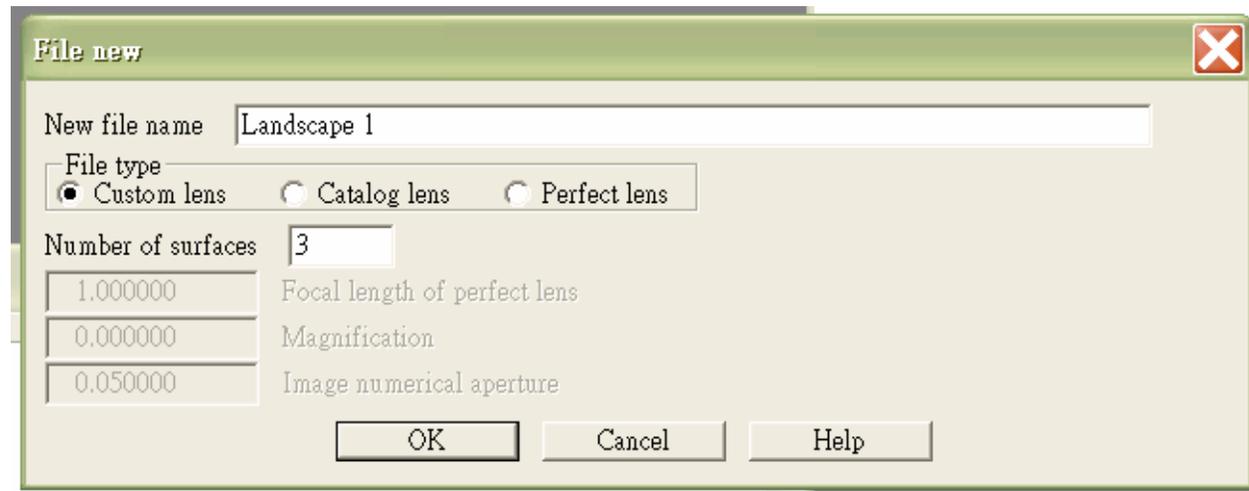
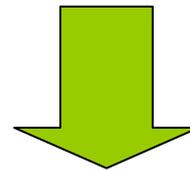
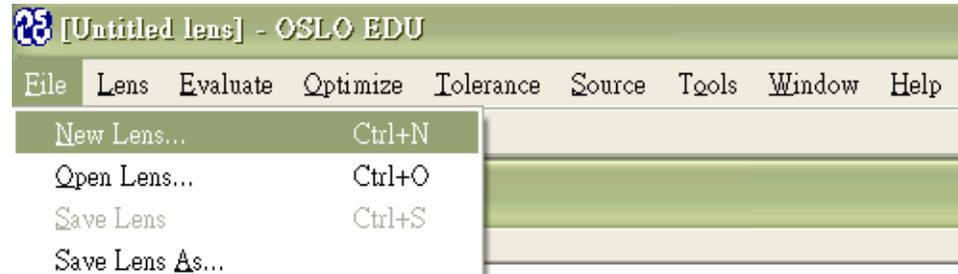
- ❑ **Lens entry** - Enter a convex-plano lens with a displaced aperture stop behind the lens.
- ❑ **Lens Drawing** - Set up the lens drawing conditions to show desired ray trajectories.
- ❑ **Optimization** - Optimize the lens so it has no coma, a focal length of 100, and covers a field of ± 20 degrees at an aperture of $f/10$.
- ❑ • **Slider-wheel design** - Attach sliders to parameters so you can analyze trade-offs.

Lens entry, 1

- ❑ beam radius = 5 mm
- ❑ field angle = 20 degree
- ❑ Convex-plano lens
 - Radius of surface 1 = 50 mm
 - Radius of surface 2 = 0 mm (∞)
 - Thickness = 4 mm
 - Material = BK7
- ❑ Initial position of aperture stop = 10 mm after the surface 2 of the convex-plano lens



Lens entry, 2



Lens entry, 3

Surface Data

Gen Setup Wavelength Variables Draw Off Group Notes

Lens: Landscape Lens Exercise Ef1 96.749205

Ent beam radius 5.000000 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	
1	<u>50.000000</u>	<u>4.000000</u>	10.290581	BK7	C
2	0.000000	<u>10.000000</u>	9.050250	AIR	
AST	0.000000	84.112075	4.346913	AIR	F
IMS	0.000000	0.000000	35.213831		F

Surface Note (N)
 Surface Control (F) General
 Coordinates (C)

Extrude aperture to form rod: No
 Surface appearance in lens drawings: Drawn
 Pen number for surface in lens drawings:

Direct specification
 Not Checked
 Checked (K)
 Pickup... (P)
 Solved (S)
 Aperture Stop (A)
 Reference Surface (R)
 Special Aperture Data... (X)

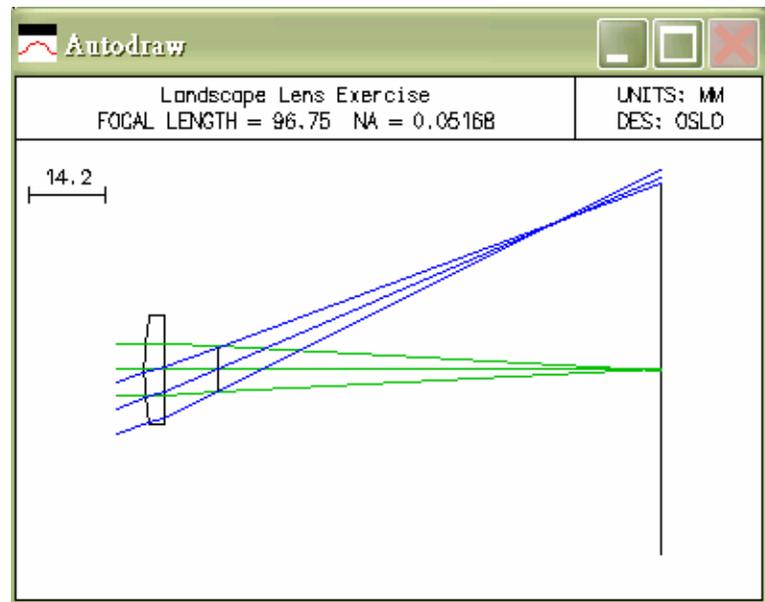
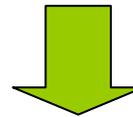
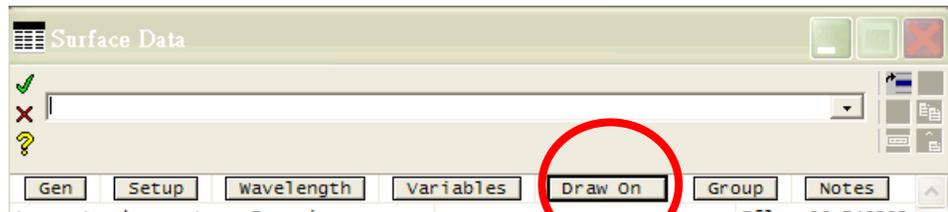
OSLO EDU
 Enter solve value:

Direct specification
 Solves (S)
 Pickups (P)
 Variable (V)
 Special variable... (V)

Axial ray height...
 Chief ray height...
 Edge thickness...

Air
 Reflect
 Reflect (hatch)
 Pickup... (P)
 Catalog (C) Schott
 Model... (M) Schott 2004
 Direct... Schott RadHard
 Ohara
 Hoya
 Corning

Lens drawing, 1



Lens drawing, 2

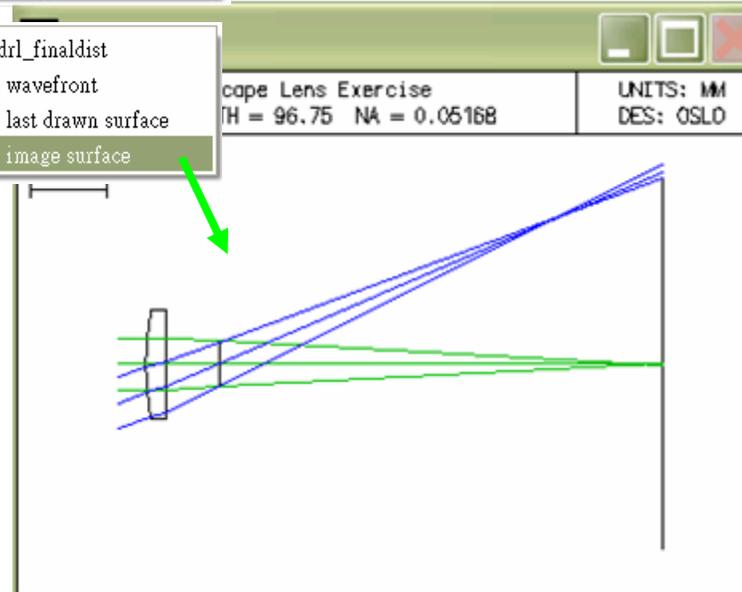
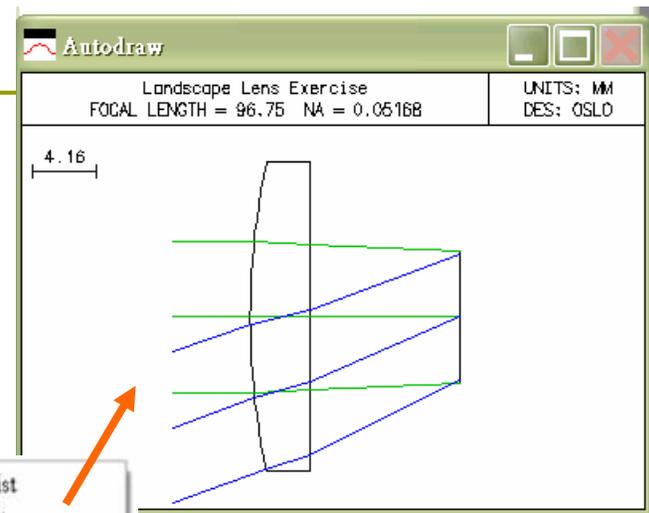
Lens Drawing Conditions < Surface Data

Initial distance: 0.000000 Final distance: 0.000000
Horizontal view angle: 240 Vertical view angle: 30
First surface to draw: 0 Last surface to draw: 0 Autodraw: YZ
X shift: 0.000000 Y shift: 0.000000 DXF/IGES view: Unconverted
Apertures: Quadrant Rings: 3 Spokes: 4 Image space rays: Image srf
Draw aperture stop: Off On Hatch back of reflectors: Off On
Shaded solid color - Red: 175 Green: 185 Blue: 250
Number of ray fans in lens drawings: 3 Points for aspheric profiles: 41

Frac Y Obj	Frac X Obj	Rays	Min Pupil	Max Pupil	Offset	FY	FX	Wvn
0.000000	0.000000	3	-1.000000	1.000000	0.000000	<input checked="" type="radio"/>	<input type="radio"/>	1
0.700000	0.000000	0	0.000000	0.000000	0.000000	<input checked="" type="radio"/>	<input type="radio"/>	1
1.000000	0.000000	3	-1.000000	1.000000	0.000000	<input checked="" type="radio"/>	<input type="radio"/>	1

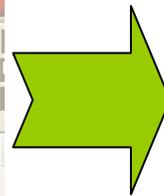
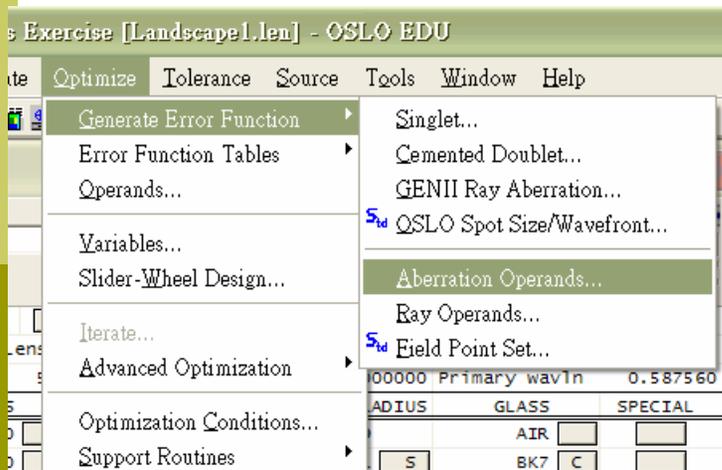
- Use defined drl_finaldist
- Draw rays to wavefront
- Draw rays to last drawn surface
- Draw rays to image surface

- Use defined drl_finaldist
- Draw rays to wavefront
- Draw rays to last drawn surface
- Draw rays to image surface



Optimization, 1

- We will define an error function that makes the focal length exactly 100 mm, and also eliminates the Seidel coma from the image.



Operands Data Editor - Surface Data

OP	MODE	WGT	NAME	DEFINITION
1	Min	0.000000	PY	OCM1
2	Min	0.000000	PU	OCM2
3	Min	0.000000	PYC	OCM3
4	Min	0.000000	PUC	OCM4
5	Min	0.000000	PAC	OCM5
6	Min	0.000000	PLC	OCM6
7	Min	0.000000	SAC	OCM7
8	Min	0.000000	SLC	OCM8
9	Min	0.000000	SA3	OCM9
10	Min	0.000000	CMA3	OCM10
11	Min	0.000000	AST3	OCM11
12	Min	0.000000	PTZ3	OCM12
13	Min	0.000000	DIS3	OCM13
14	Min	0.000000	SAS	OCM14
15	Min	0.000000	CMA5	OCM15
16	Min	0.000000	AST5	OCM16
17	Min	0.000000	PTZ5	OCM17
18	Min	0.000000	DIS5	OCM18
19	Min	0.000000	SA7	OCM19
20	Min	0.000000	TOTAL_SPH	OCM20
21	Min	0.000000	EFL	OCM21

Optimization, 2

PU operand is the axial ray slope leaving the lens.

OP	MODE	WGT	NAME	DEFINITION
1	Min	0.000000	PU	OCM2
2	Min	0.000000	CMA3	OCM10

Coma

Beam radius = 5 mm
Effective focal length = 100mm



f-number = 10
PU = 0.05 radian

In OSLO, all operands are targeted to zero.

OP	MODE	WGT	NAME	DEFINITION
1	Min	1.000000	PU	OCM2+0.05
2	Min	1.000000	CMA3	OCM10

Optimization, 3



A screenshot of the "Operands" window, showing a table of operand values and error function values. The table has the following columns: OP, MODE, WGT, NAME, VALUE, %CNTRB, and DEFINITION. The data is as follows:

OP	MODE	WGT	NAME	VALUE	%CNTRB	DEFINITION
O 1	M	1.000000	PU	-0.001680	49.59	OCM2+0.05
O 2	M	1.000000	CMA3	0.001694	50.41	OCM10

Below the table, the text "MIN RMS ERROR: 0.001687" is displayed.

The current operand values, together with the current value of the error function, will be shown.

Optimization, 4

Surface Data

Gen Setup Wavelength Variables Draw On Group Notes

Lens: Landscape Lens Exercise Efl 96.749205

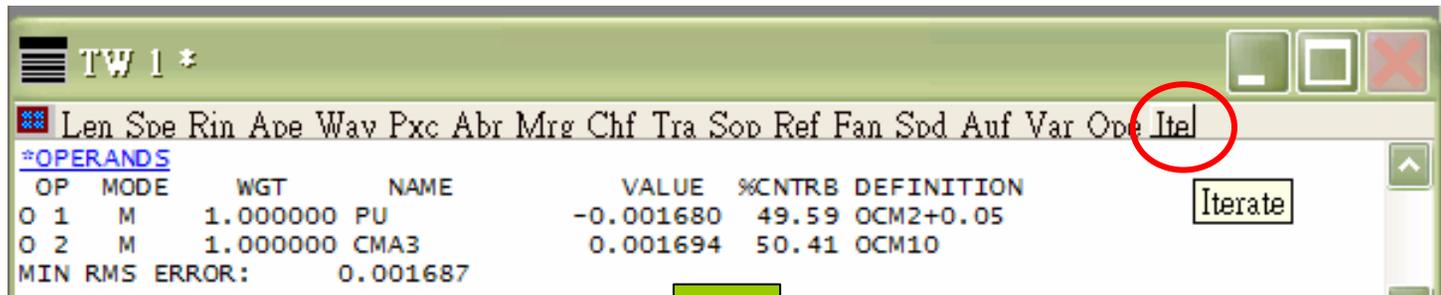
Ent beam radius 5.000000 Field angle 20.000000 Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+20	3.6397e+19	AIR	
1	50.000000	4.000000	10.290581	BK7	C
2	0.000000	10.000000	9.050250	AIR	
AST	0.000000	84.112075	4.346913	AIR	F
IMS	0.000000	0.000000	35.213831		F

- Direct specification
- Solves (S)
- Curvature pickup... (P)
- Minus curvature pickup... (P)
- Variable (V)
- Special variable... (V)

Optimization, 5

Before doing optimization, close the lens spreadsheet (Green check) and immediately re-open it.

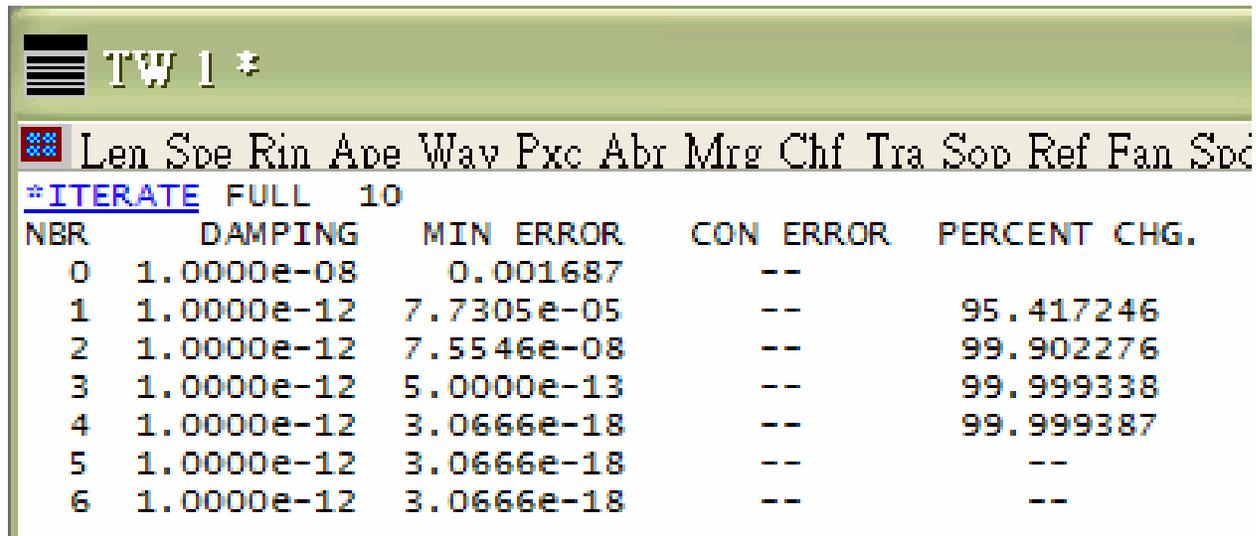


```

TW 1 *
*** Len Spc Rin Ape Way Pxc Abr Mrg Chf Tra Ssp Ref Fan Spd Auf Var Ope Ite
*OPERANDS
OP  MODE    WGT     NAME                VALUE  %CNTRB  DEFINITION
O 1    M      1.000000  PU                  -0.001680  49.59  OCM2+0.05
O 2    M      1.000000  CMA3                 0.001694  50.41  OCM10
MIN RMS ERROR:      0.001687

```

The screenshot shows a window titled "TW 1 *". The main content area displays a list of operands. The "Iterate" button is circled in red. A green arrow points from this window down to the next screenshot.



```

TW 1 *
*** Len Spc Rin Ape Way Pxc Abr Mrg Chf Tra Ssp Ref Fan Spd
*ITERATE FULL 10
NBR      DAMPING      MIN ERROR      CON ERROR      PERCENT CHG.
0  1.0000e-08      0.001687      --
1  1.0000e-12      7.7305e-05      --      95.417246
2  1.0000e-12      7.5546e-08      --      99.902276
3  1.0000e-12      5.0000e-13      --      99.999338
4  1.0000e-12      3.0666e-18      --      99.999387
5  1.0000e-12      3.0666e-18      --      --
6  1.0000e-12      3.0666e-18      --      --

```

The screenshot shows the same window after the iteration process. The main content area displays the results of the iteration process, showing the number of iterations (NBR), damping factor, minimum error, convergence error, and percent change.

Optimization, 6

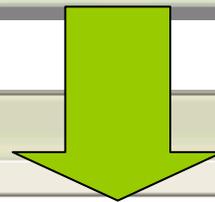
Surface Data

Gen Setup Wavelength Variables Draw On Group Notes

Lens: Landscape Lens Exercise Ef1 96.749205

Ent beam radius 5.000000 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	
1	50.000000 V	4.000000	10.290581 S	BK7 C	
2	0.000000	10.000000 V	9.050250 S	AIR	
AST	0.000000	84.112075 S	4.346913 AS	AIR	F
IMS	0.000000	0.000000	35.213831 S		F



Surface Data

Gen Setup Wavelength Variables Draw On Group Notes

Lens: Landscape Lens Exercise Ef1 100.000000

Ent beam radius 5.000000 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	
1	51.680011 V	4.000000	9.856783 S	BK7 C	
2	0.000000	9.135802 V	8.637010 S	AIR	
AST	0.000000	88.227067 S	4.411353 AS	AIR	F
IMS	0.000000	0.000000	36.397023 S		F

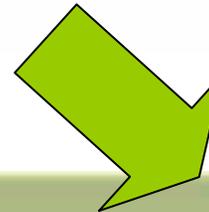
Optimization, 7

TW 1 *

*** Len Spc Rin Ape Wav Pxc **Abr** Mrg Chf Tra Sop Ref Fan Spd Auf Var Ope Ite

*ITERATE FULL 10

NBR	DAMPING	MIN ERROR	CON ERROR	PERCENT CHG.
0	1.0000e-08	0.001687	Aberrations	
1	1.0000e-12	7.7305e-05	--	95.417246
2	1.0000e-12	7.5546e-08	--	99.902276



TW 1 *

*** Len Spc Rin Ape Wav Pxc Abr Mrg Chf Tra Sop Ref Fan Spd Auf Var Ope Ite

*PARAXIAL TRACE

SRF	PY	PU	PI	PYC	PUC	PIC
4	--	-0.050000	-0.050000	36.397023	0.412538	0.412538

*CHROMATIC ABERRATIONS

SRF	PAC	SAC	PLC	SLC
SUM	-0.077222	-0.053466	0.069914	0.048406

*SEIDEL ABERRATIONS

SRF	SA3	CMA3	AST3	PTZ3	DIS3
SUM	-0.013612	4.3368e-18	-0.313405	-0.218345	1.101908

*FIFTH-ORDER ABERRATIONS

SRF	SA5	CMA5	AST5	PTZ5	DIS5	SA7
SUM	-9.6466e-05	-5.9253e-05	-0.020638	0.017274	0.070480	-7.7081e-07

Slider-wheel design, 1

- A landscape lens is normally a meniscus form. Next we show how to use OSLO's slider-wheel window to find the optimum form.

The screenshot shows the OSLO software interface. The main window is titled "Landscape Lens Exercise [Landscape1.len] - OSLO". Below the menu bar, there are icons for various functions. The "Surface Data" window is open, showing a "Slider-wheel Setup < Surface Data" dialog. The dialog has a green header and a list of parameters. A dropdown menu is open, showing a list of parameters for "Curvature (CV)".

Slider-wheel Setup < Surface Data

Curvature (CV)

- Curvature pickup multiplier (CVM)
- Conic constant (CC)
- Thickness (TH)
- X decentration (DCX)
- Y decentration (DCY)
- Z decentration (DCZ)
- Alpha tilt angle (TLA)
- Beta tilt angle (TLB)
- Gamma tilt angle (TLC)
- Tilt vertex offset in x (TOX)
- Tilt vertex offset in y (TOY)
- Tilt vertex offset in z (TOZ)

No Internal evaluation
 Draw only Ray-intercept OPD Field sag Spot diagram Long. SA
Graphics scale: 1 Field point at FBY All points
Number of sliders: Use drag processing

Surf	Cfg	Item	value
<input type="text" value="2"/>	<input type="text" value="0"/>	Curvature (CV)	0.000000
<input type="text" value="4"/>	<input type="text" value="0"/>	Curvature (CV)	0.000000

Enable sw_callback CCL function Level
Setup name: Save setup

Slider-wheel design, 2

The screenshot displays the Zemax OpticStudio interface for a lens design exercise. The main window is titled "Landscape Lens Exercise [Landscape1.len] - OSLO EDU". The menu bar includes File, Lens, Evaluate, Optimize, Tolerance, Source, Tools, Window, and Help. The "Surface Data" window is open, showing the following parameters:

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+20	3.6397e+19	AIR	
1	51.680011	4.000000	9.856783	BK7	C
2	0.000000	9.135802	8.637010	AIR	
AST	0.000000	88.227067	4.411353	AS	F
IMS	0.000000	0.000000	36.397023	S	F

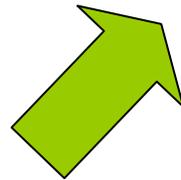
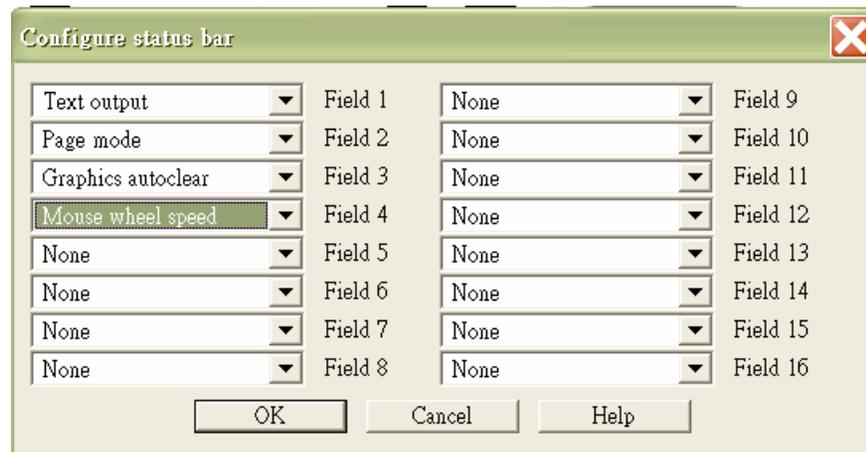
The "Slider Window" shows two sliders for CV 2 and CV 4, both set to 0.000000. The "TW 1 *" window shows the lens layout with a menu bar: Len Spe Rin Ape Way Pxc Abr Mrz Chf Tra Sop Ref Fan Spd Auf Var Ope Ite. The "GW 31" window displays a ray plot showing an elliptical spot. The "GW 32 *" window displays a ray plot showing a fan of rays.

Title windows

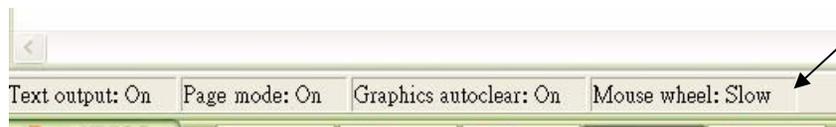
The elliptical shape is characteristic of a system with astigmatism, but no coma.

Text output: On | Page mode: On | Graphics autoclear: On | Mouse wheel: Slow

Slider-wheel design, 3



You change between fast and slow by clicking the mouse wheel itself.

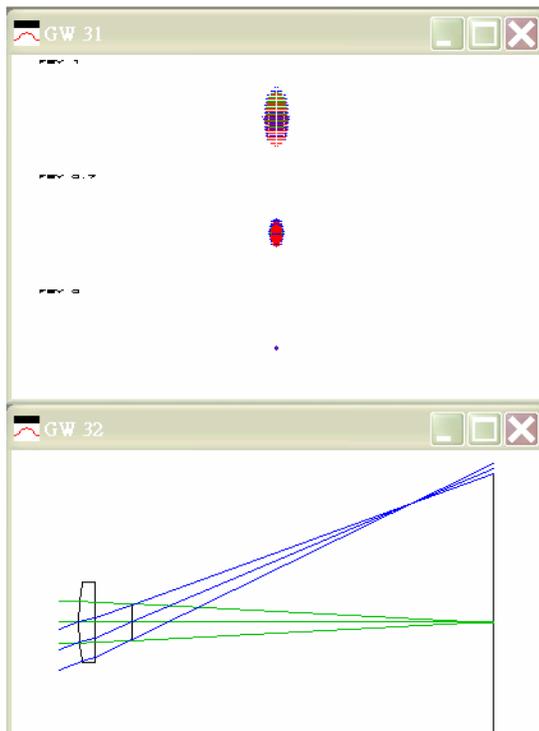


double click on the status bar in the main OSLO window.

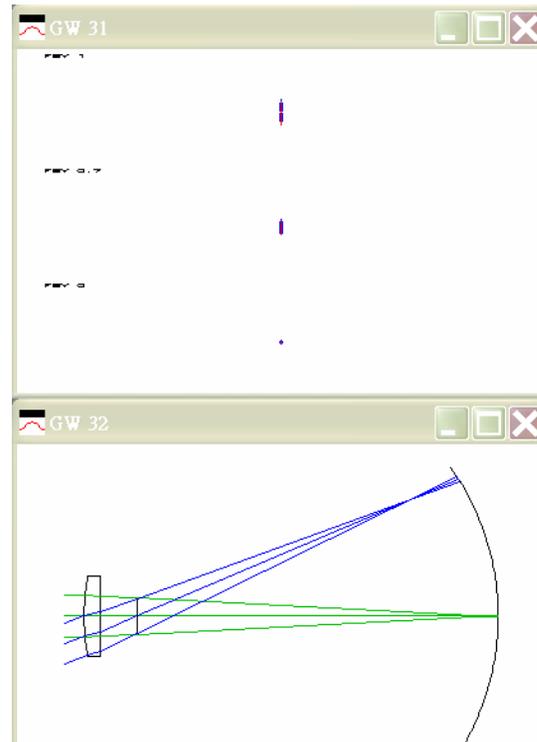
Slider-wheel design, 4

- ❑ If you make CV[2] negative, the lens becomes positive and the focal length gets smaller. The image quality changes, since the system is no longer free of coma. If you make CV[2] positive, the lens becomes first a meniscus with a long focal length, but eventually the lens becomes negative.
- ❑ When you change CV[4], you see that by making it negative, you can improve the size of the image off-axis, and in fact you can find a position where there is a line focus in the horizontal direction (tangential focus), or the vertical direction (sagittal focus). This is indicative of a system with no coma.

Slider-wheel design, 5

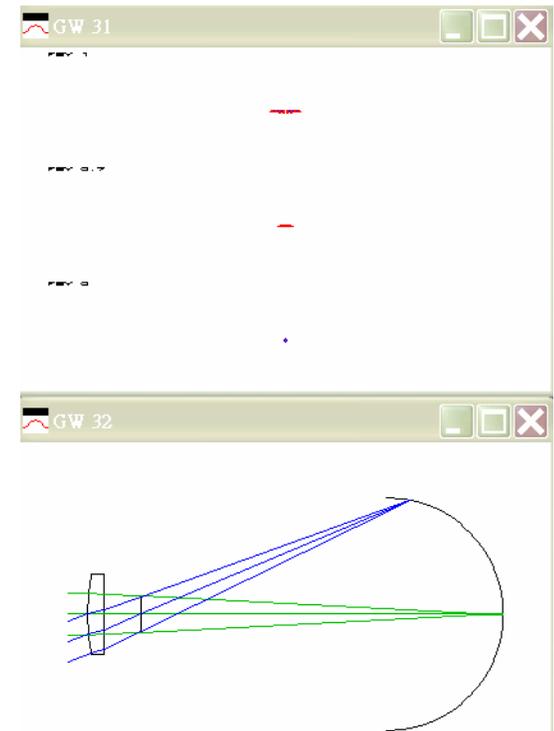


$CV2=0, CV4=0$



$CV2=0, CV4=-0.016$

sagittal focus

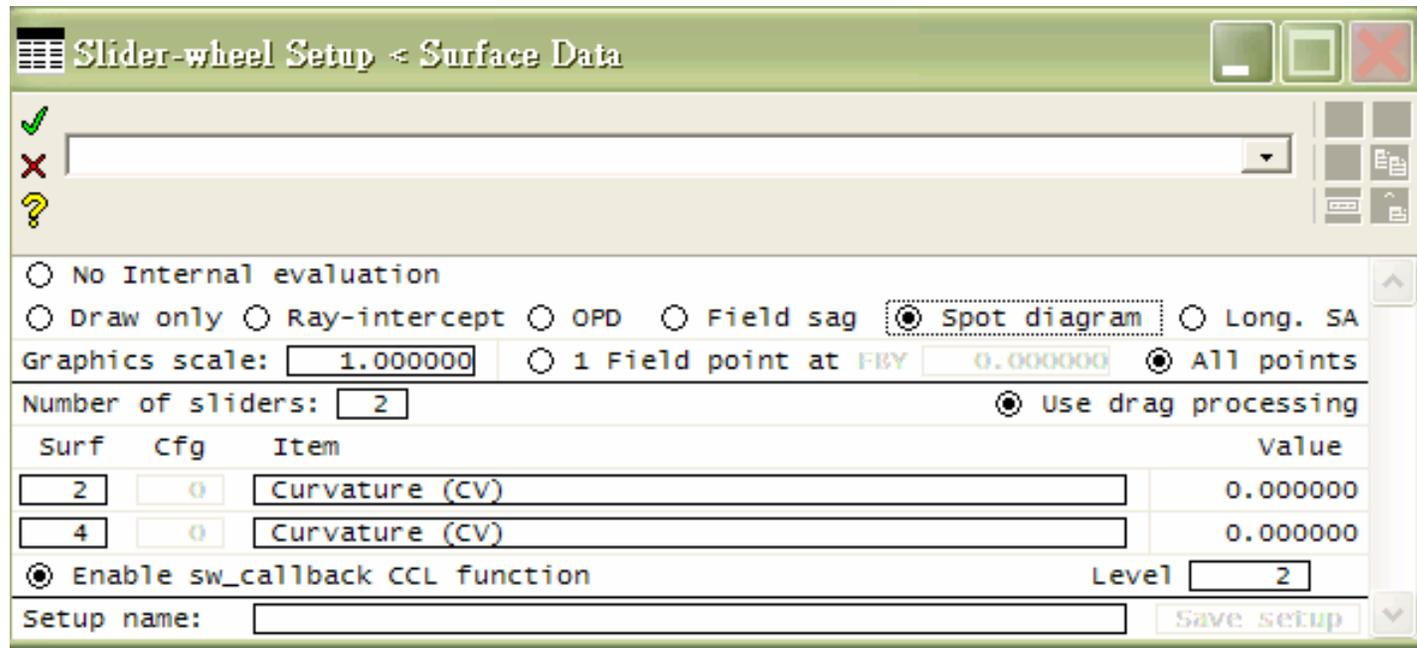


$CV2=0, CV4=-0.035$

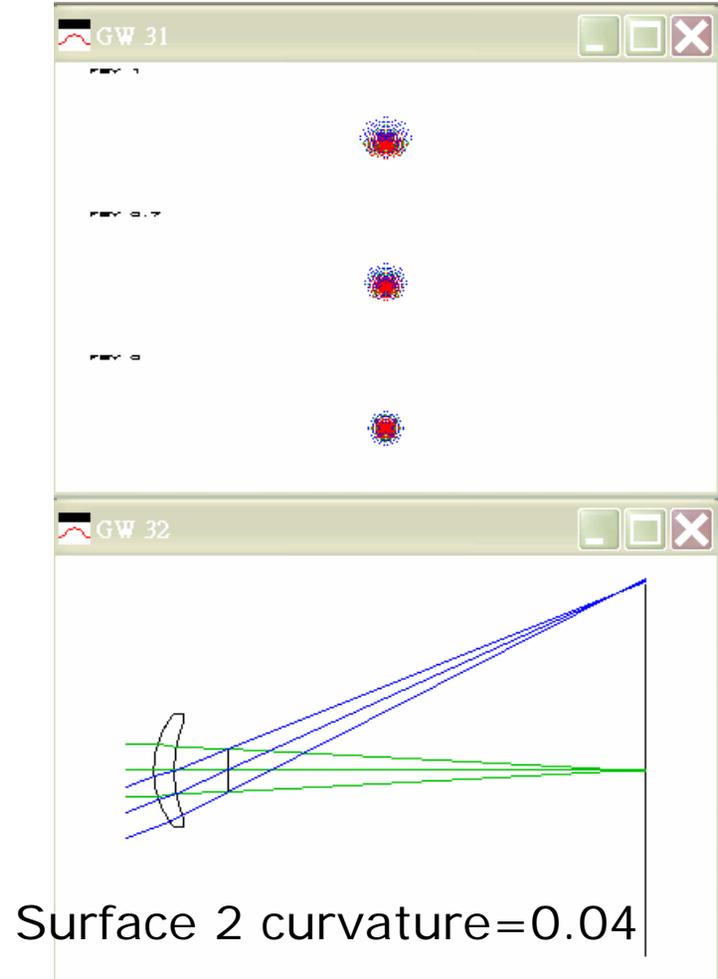
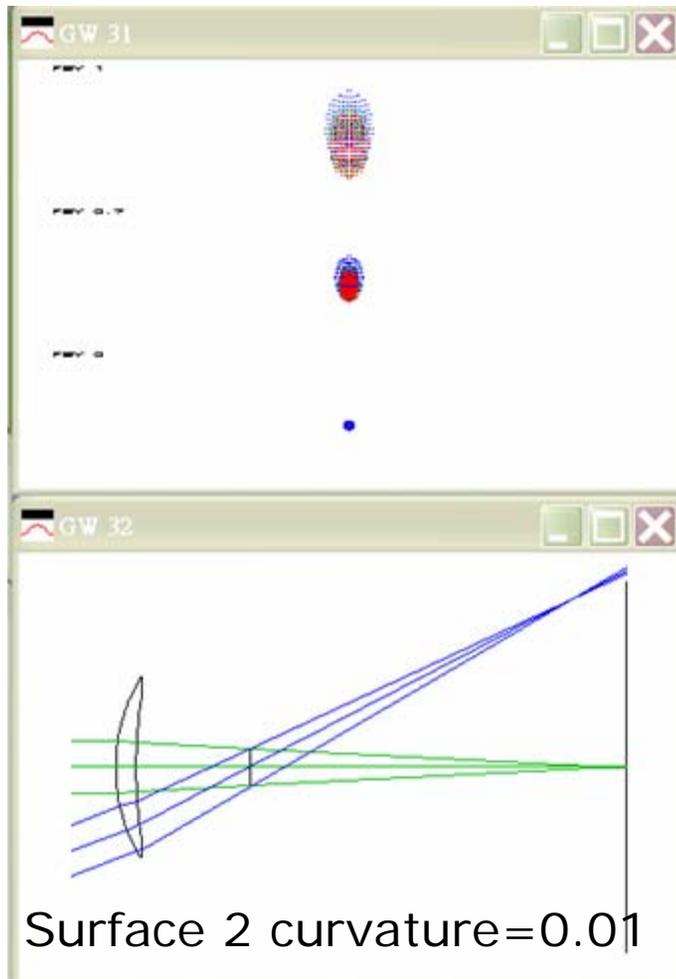
tangential focus₂

Slider-wheel design, 6

- The real power of sliders in OSLO comes when you allow the program to re-optimize the system as you drag a slider.



Slider-wheel design, 7



Slider-wheel design, 8

- The stop initially moves away from the lens as it becomes a meniscus, but as the bending becomes larger, the stop shift reverses and the aperture stop moves back towards the lens.

Optical materials

- The most important is often the ***dispersion***, but many other attributes must also be considered, such as ***thermal characteristics, weight, mechanical*** and ***chemical properties, availability,*** and ***cost***.

Dispersion, 1

- Sellmeier formula

$$n^2(\lambda) = 1.0 + \frac{b_1\lambda^2}{\lambda^2 - c_1} + \frac{b_2\lambda^2}{\lambda^2 - c_2} + \frac{b_3\lambda^2}{\lambda^2 - c_3}$$

- Laurent series, sometimes called the Schott formula

$$n^2(\lambda) = A_0 + A_1\lambda^2 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} + \frac{A_4}{\lambda^6} + \frac{A_5}{\lambda^8}$$

- where λ is the wavelength in μm .

Dispersion, 2

- **Conrady** found that in the visible portion of the spectrum a good fit could be obtained using the formula

$$n(\lambda) = n_0 + \frac{A}{\lambda} + \frac{B}{\lambda^{3.5}}$$

- **Buchdahl** introduced a *chromatic coordinate* for accurately characterizing the refractive index.

$$\omega(\lambda) = \frac{\lambda - \lambda_0}{1 + 2.5(\lambda - \lambda_0)}$$

$$n(\omega) = n_0 + v_1\omega + v_2\omega^2 + v_3\omega^3 + \dots$$

- where the wavelength λ is expressed in μm and λ_0 is a reference wavelength, typically the d line ($0.5876 \mu\text{m}$) for visible light.

V number or Abbe number

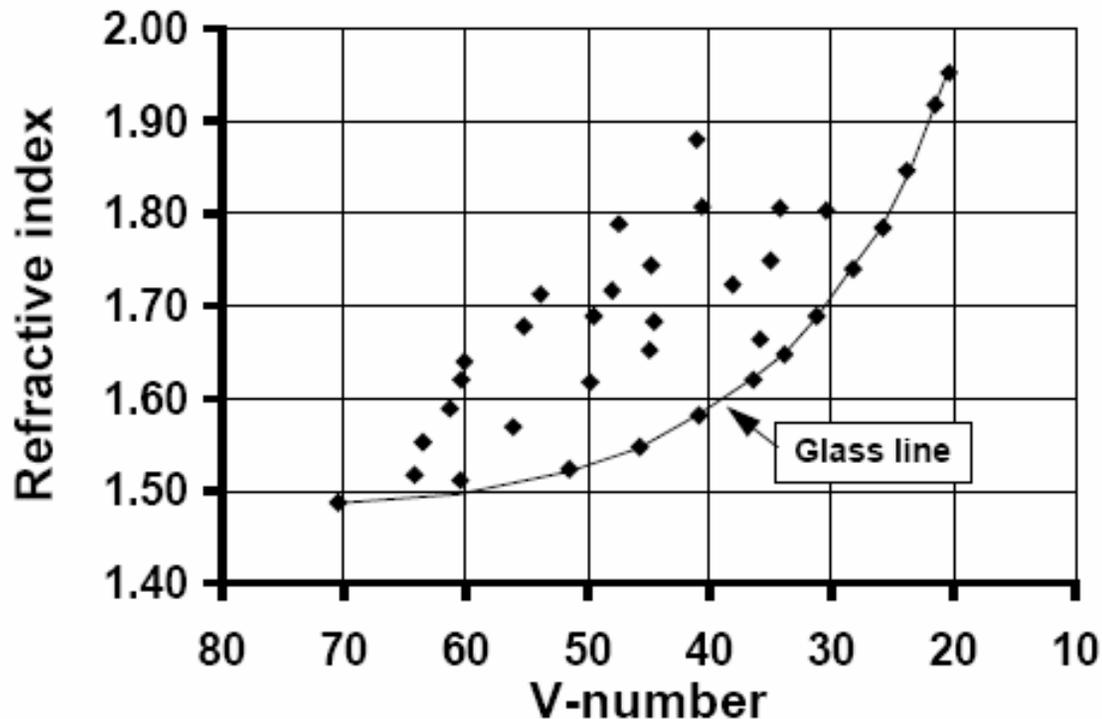
- V (or ν) number, or Abbe number, is defined by

$$V \equiv \frac{n_d - 1}{n_F - n_C}$$

- n_d : the refractive index at the helium d (0.5876 μm) line
 - n_F : the refractive index at the hydrogen F (0.4861 μm) line
 - n_C : the refractive index at the hydrogen C (0.6563 μm) line.
- In OSLO, wavelength 1 is taken to be the primary wavelength, wavelength 2 to be the short wavelength, and wavelength 3 to be the long wavelength.

Glass map, 1

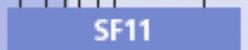
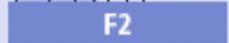
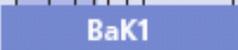
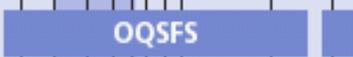
- The characteristics of optical glasses are often displayed on a two-dimensional graph, called a *glass map*.



Glass map, 2

- ❑ Most glasses lie along or near a line forming the lower right boundary of the region occupied by optical glasses. This line is called the *glass line*.
- ❑ The availability of optical glasses that are located a considerable distance above the glass line gives the optical designer considerable flexibility **in correcting the chromatic (and other) aberrations** of optical systems.
- ❑ However, when an arbitrary choice is to be made, the glass chosen should be one on or near the glass line, since such glasses are **cheaper** and **more readily available**.

Material Properties Overview (Melles Griot), 1

Material	Usable Transmission Range	Index of Refraction	Features
BK7 N-BK7		1.52 @ 0.55 μm	Excellent all-around lens material provides broad transmission with excellent mechanical characteristics
LaSFN9		1.86 @ 0.55 μm	High-refractive-index flint glass provides more power with less curvature
SF11		1.79 @ 0.55 μm	High-refractive-index flint glass provides more power with less curvature
F2		1.62 @ 0.55 μm	Material represents a good compromise between higher index and acceptable mechanical characteristics
BaK1 N-BaK1		1.57 @ 0.55 μm	Excellent all-around lens material, but has weaker chemical characteristics than BK7
Optical-Quality Synthetic Fused Silica (OQSFS)		1.46 @ 0.55 μm	Material provides good UV transmission and superior mechanical characteristics
UV-Grade Synthetic Fused Silica (UVGSFS)		1.46 @ 0.55 μm	Material provides excellent UV transmission and superior mechanical characteristics
Optical Crown Glass		1.52 @ 0.55 μm	This lower tolerance glass can be used as a mirror substrate or in non-critical applications

0.1 0.5 1.0 5.0 10.0
WAVELENGTHS IN μm

Material Properties Overview (Melles Griot), 1

Material	Usable Transmission Range	Index of Refraction	Features
Low-expansion borosilicate glass (LEBG)		1.48 @ 0.55 μm	Excellent thermal stability, low cost, and homogeneity makes LEBG useful for high-temperature windows, mirror substrates, and condenser lenses
Sapphire		1.77 @ 0.55 μm	Excellent mechanical and thermal characteristics make it a superior window material
Zinc Selenide		2.40 @ 10.6 μm	Zinc selenide is most popular for transmissive IR optics; transmits visible and IR, and has low absorption in the red end of the spectrum
Calcium Fluoride		1.399 @ 5 μm	This popular UV excimer laser material is used for windows, lenses, and mirror substrates
ZERODUR®		1.55 @ 0.55 μm	Highly homogeneous glass-ceramic with near-zero coefficient of thermal expansion is ideal for mirror substrates for stringent applications
Calcite		1.66 @ 0.55 μm	Naturally occurring negative uniaxial crystal with pronounced birefringence makes this material suitable for polarizing prisms
α -BBO		1.66 @ 0.55 μm	Pronounced birefringence, transmission to 189 nm and high-damage threshold properties of this material are ideal for polarizing prisms

0.1 0.5 1.0 5.0 10.0
WAVELENGTHS IN μm

Lens Design and Optimization Procedure

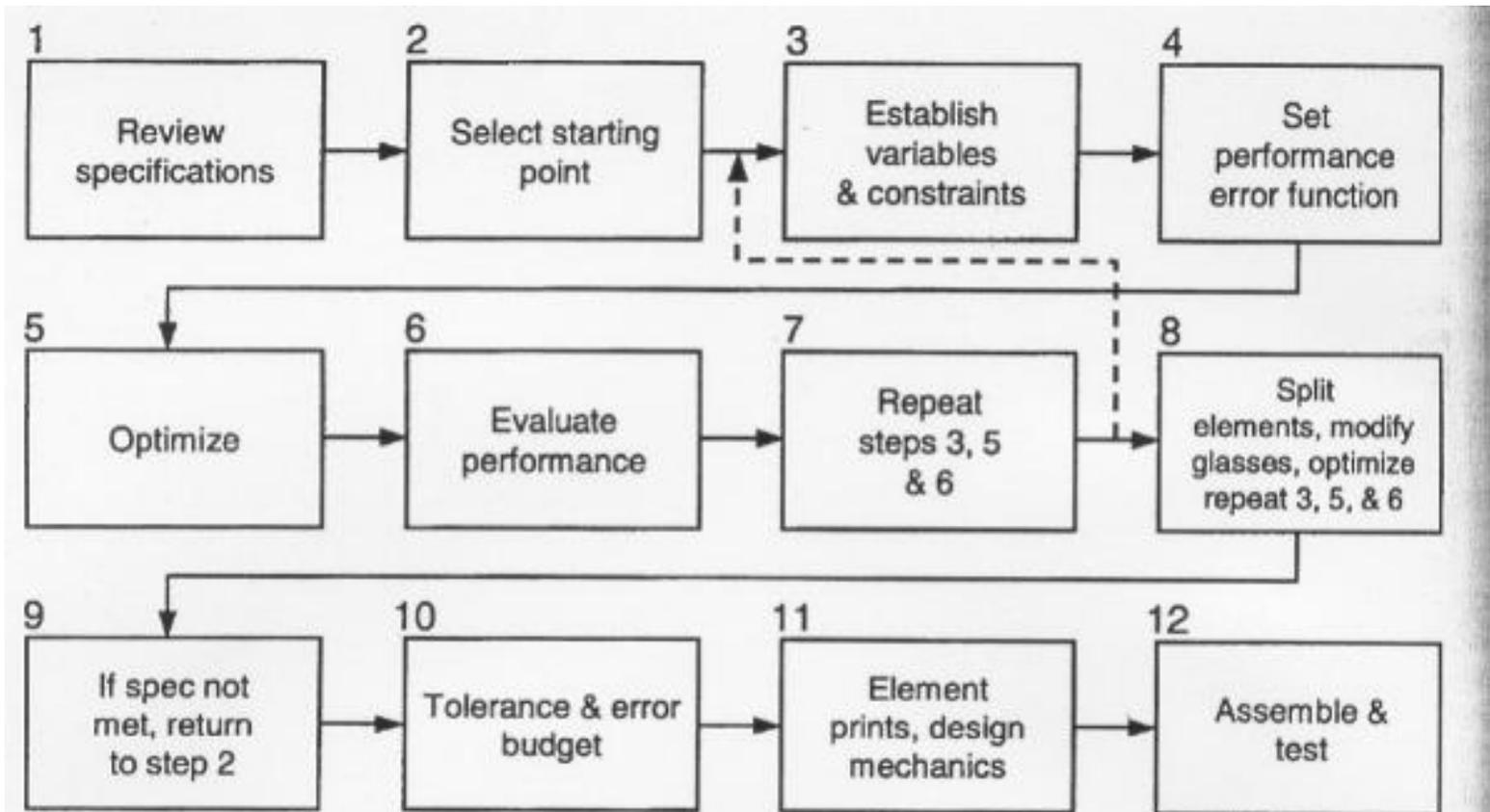
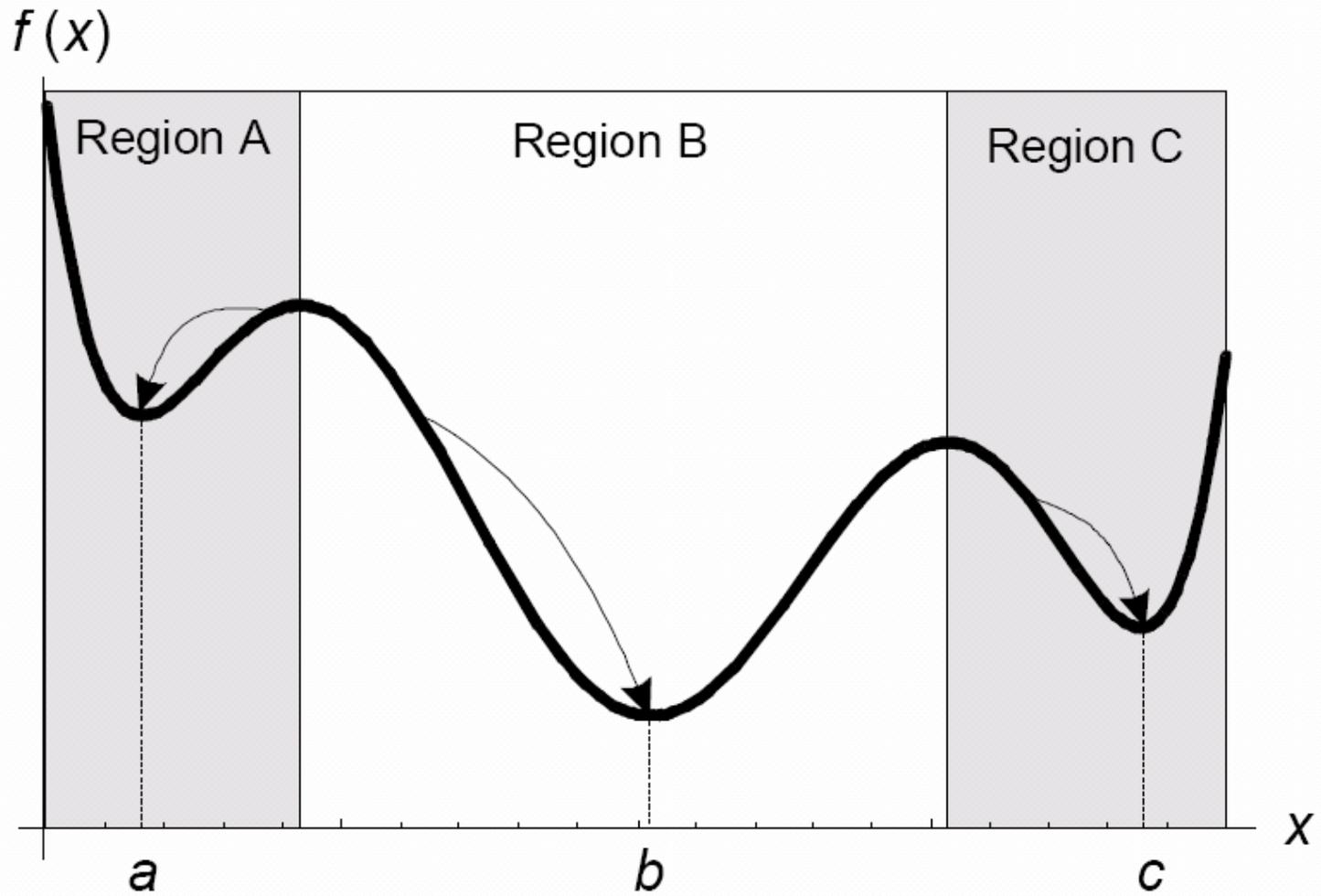


Figure 9.2 Lens Design and Optimization Procedure

Optimization, 1

- ❑ ***optimization*** in optical design refers to the improvement of the performance of an optical system by changing the values of a subset of the system's constructional parameters (*variables*).
- ❑ The variables are quantities such as surface curvatures, element and air-space thicknesses, tilt angles, etc.
- ❑ The system's performance is measured by a **user-defined error function**, which is the weighted sum of squares of *operands*, that represents an estimate of the difference in performance between a given optical system and a system that meets all the design requirements.

Optimization, 2



Approach to optimization

- the user chooses initial values for the variables and an optimization algorithm is applied that repeatedly attempts to find new values for the variables that yield ever lower error function values.
- ***This approach depends heavily upon the choice of the starting point.***
- ***Starting points are typically determined by experience or by finding an existing design with properties similar to those desired.***
- Most of optimization methods employed in optical design are *least-squares methods*,

Default tolerances in OSLO

Property	Maximum dimension of part (mm)			
	Up to 10	Over 10 Up to 30	Over 30 Up to 100	Over 100 Up to 300
Edge length, diameter (mm)	± 0.2	± 0.5	± 1.0	± 1.5
Thickness (mm)	± 0.1	± 0.2	± 0.4	± 0.8
Angle deviation of prisms and plate	± 30'	± 30'	± 30'	± 30'
Width of protective chamfer (mm)	0.1 – 0.3	0.2 – 0.5	0.3 – 0.8	0.5 – 1.6
Stress birefringence (nm/cm)	0/20	0/20	–	–
Bubbles and inclusions	1/3x0.16	1/5x0.25	1/5x0.4	1/5x0.63
Inhomogeneity and striae	2/1;1	2/1;1	–	–
Surface form tolerances	3/5(1)	3/10(2)	3/10(2) 30 mm diameter	3/10(2) 60 mm diameter
Centering tolerances	4/30'	4/20'	4/10'	4/10'
Surface imperfection tolerances	5/3x0.16	5/5x0.25	5/5x0.4	5/5x0.63

These tolerance values are taken from the ISO 10110 standard.

Typical optical fabrication tolerances

	Surface Quality	Diameter, mm	Deviation (concentricity) min	Thickness, mm	Radius	Regularity (asphericity)	Linear Dimension, mm	Angles
Low cost	120-80	± 0.2	> 10	± 0.5	Gage	Gage	± 0.5	Degrees
Commercial	80-50	± 0.07	3-10	± 0.25	10 Fr	3 Fr	± 0.25	± 15'
Precision	60-40	± 0.02	1-3	± 0.1	5 Fr	1 Fr	± 0.1	± 5'-10'
Extraprecise	60-40	± 0.01	< 1	± 0.05	1 Fr	½ Fr	As req'd.	Seconds
Plastic	80-50		1	± 0.02	10 Fr	5 Fr	0.02	minutes

Ref: W. Smith, Optical modern engineering