OSLO

Optics Software for Layout and Optimization

User Guide

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TRADEMARKS

Preface

Since its inception at the Institute of Optics at the University of Rochester, the software written by Doug Sinclair has played a key role in the teaching as well as in the performance of optical design. So OSLO, perhaps more than any other optical design software, shows signs of its origins in a teaching establishment. The flexibility of the user interface, the open source nature of much of the code, the CCL programming language which is very similar to C, and real capability of OSLO EDU, the free version of OSLO, to carry out real design tasks, make it the ideal choice for the teaching environment.

This manual has been written to supplement the current documentation for commercial users of OSLO software. Its second aim is to provide a gentle introduction to the experience of optical design for those who have only just downloaded OSLO EDU from the internet. The first chapter is written expressly for them. More experienced designers may wish to skip straight to the second chapter.

Chapter 1 - Your first OSLO session

Introduction

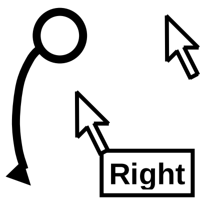
This chapter gives a click-by-click description of how OSLO can be used to carry out a very simple task involving synthesis, analysis, and optimization of a spherical concave mirror. It is in general applicable to all editions of OSLO, including OSLO EDU. This means that more advanced facilities, which may only be available in OSLO Standard and Premium editions, are not included.

The exercise will demonstrate the two main modes of calculation:

- the geometrical approximation, in which light is treated as a ray, or the path of a photon
- the physical mode of calculation, in which the light is treated as propagating as a wave front, and the results take account of the effects of diffraction.

Symbols used in this chapter

A left-click on the mouse is indicated by a white arrow, and a right-click by the box with the word "Right". If a drop-down menu is selected by a left-click, then it is represented by a black circle and arrow.



Step by step instructions are marked with bullet points. Instructions about what to do if things go badly wrong are in *italics* and labeled ***HELP!*** .

Anything typed from the keyboard (whether as a command or as an entry in a dialog box) is shown in `this typeface`.

Labels and headers in spreadsheets and dialog boxes are given in **this typeface.**

Buttons to be clicked are shown in **gray** .

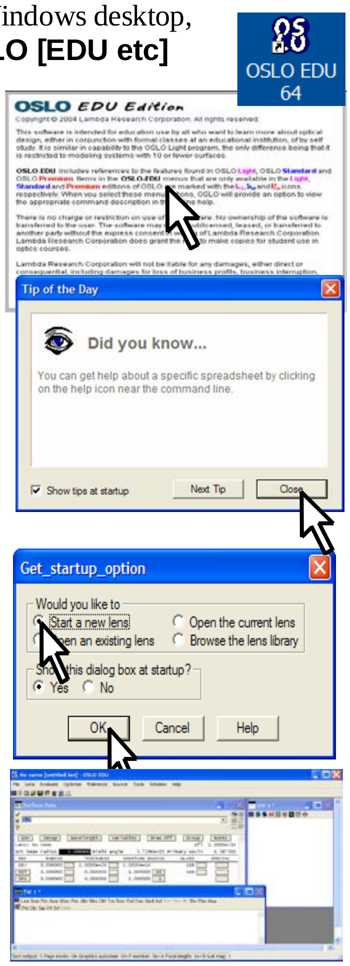
Check-boxes (called "radio buttons" in the documentation) are shown like this: ⦿

Messages which appear whenever the cursor hovers above an icon are shown in a shaded box. These are known as tooltips.

Tooltips

Questions and answers, representing a typical dialog between a lens designer and the customer, are given in **bold type.**

Running OSLO

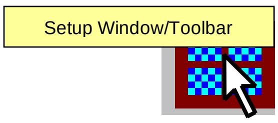


- *EITHER* click on the shortcut icon on the desktop in the Windows desktop, *OR* click on **Start ►All Programs ► OSLO►OSLO [EDU etc] Edition...**
  OR locate the .exe file in **C:\Program Files\OSLO** (e.g. **osloedu.exe**) - in some installations the directory name is **Lambda Research\OSLO**).
  - The program opens with an introductory dialog box. Click anywhere in the box to close it.
  - If a message about re-building the CCL database appears, click on **OK**
- The “Tip of the Day” is a useful tutorial for new users. Click on **Close** Alternatively it can be suppressed permanently by removing the tick from the box in the bottom left corner.
- The **Get_startup_option** window opens.
- Choose the default option: ⦿**Start a new lens** and click on **OK**
- The OSLO main window should now appear, similar in appearance to that shown here. We will now discuss the individual components of this window in detail.

The user interface

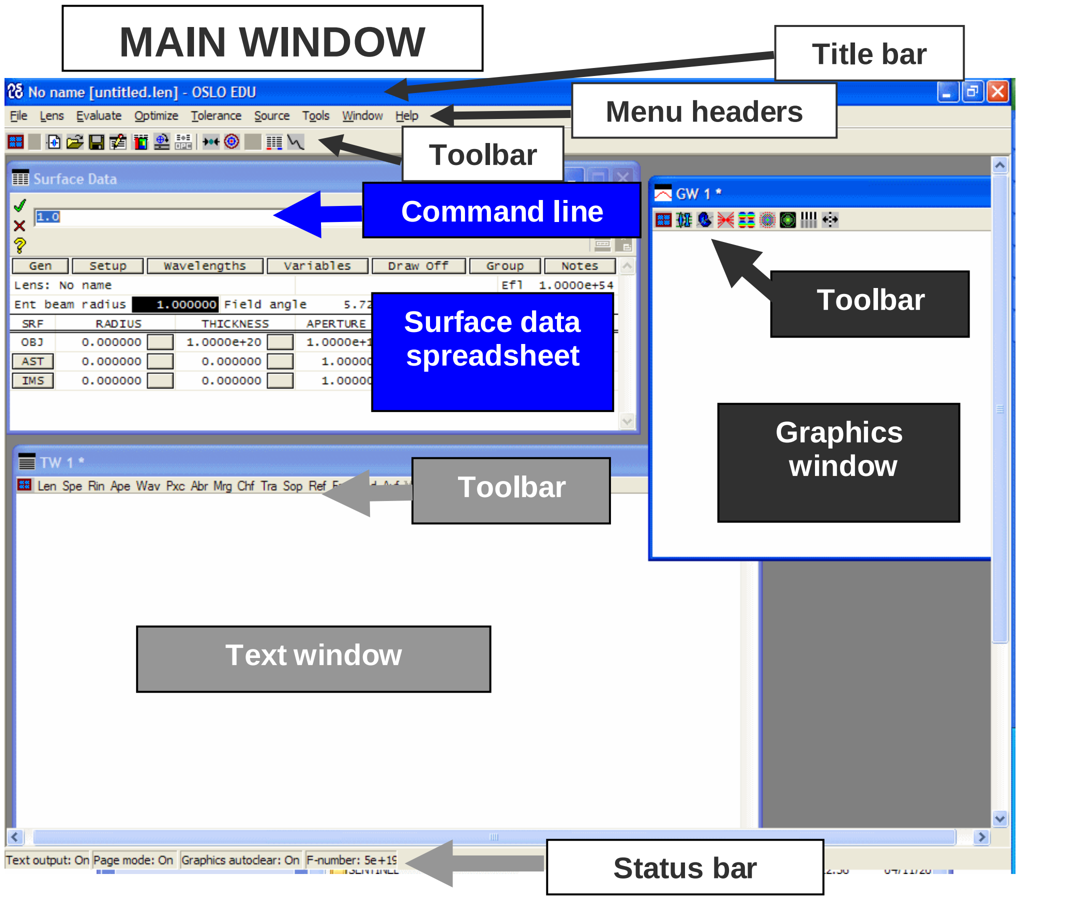
A number of terms are defined here, and given in **bold** print. At the top of the **main window** in the blue border is the **title bar**, which gives the lens identifier, the file name under which the current lens was last saved, and the edition of OSLO currently running.

Beneath this lies a row of **menu headers**, **File, Lens, Evaluate,** etc, each of which its own drop-down menu has. Many of the program commands can be accessed through these menus. The last of the menu headers is **Help** which gives access to the on-line documentation. In Windows, this can also be accessed via the F1 key on the keyboard.

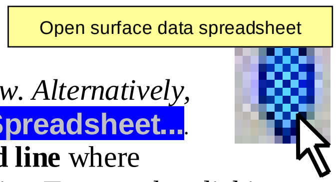


Below that is a row of **icons** forming the **main window toolbar**, which give one-click access to the most frequently used control functions. The first of these is the **Setup Window/Toolbar** icon which gives access to a list of further groups of icons which can be added to the toolbar. Other icons are to **Open surface data spreadsheet, Open a new lens, Open an existing lens, Save the current lens, Open the standard text editor,** etc. Each icon has a description of its function which pops up as a **tooltip** when the cursor is placed over the icon.

At the bottom of the main window, there is a **status bar** which can be expanded and customized by the user. This will be described in chapter 2.



The window which opens in the top left hand corner is called the **surface data spreadsheet.** This is the area where all the properties of the lens and its working conditions are defined. Entering data into this spreadsheet is described in chapter 4. Other spreadsheets are available, but only one spreadsheet can be open at a time.

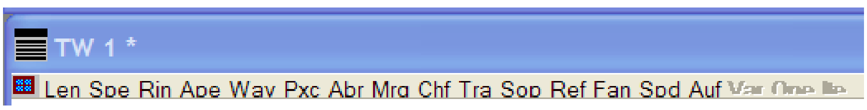


HELP! *If the surface data spreadsheet does not open, click on the blue lens icon on the left of the toolbar in the main window. Alternatively, select from the* **Lens** *menu header the option* **Surface Data Spreadsheet...**. Immediately above the surface data spreadsheet is the **command line** where **`OSLO commands`** are typed. They are executed either by pressing **Enter** or by clicking on the green tick:

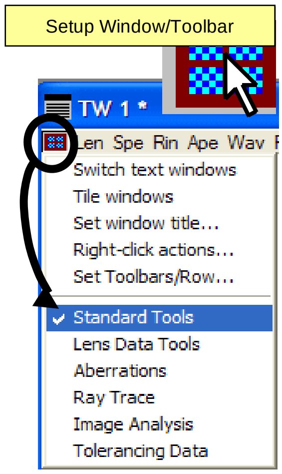
Online documentation for any command may be accessed by typing the command in the command line, and then pressing the yellow question mark beside it.

If no command is entered the documentation for any currently open spreadsheet is given.

Below the command line there is a **message area**, and on the right hand end there is the **history button**. The command line is described in detail in chapter 3.



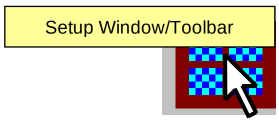
There should also be a **text window** visible. This is where printed output is directed. Along the top of this there lays a **toolbar** consisting of a row of text labels, which are OSLO commands, executed by clicking. Numerical analysis is described in chapter 6.



HELP! *If the text window toolbar does not look like the one in the diagram, click on the* **Setup Window/Toolbar** *icon in the top left-hand corner of the text window, and select* **Standard Tools** *from the menu. Any or all of the toolbar groups may be selected for a text window. Either one or two, but not more, text windows can be shown at a time.*

The user may create additional toolbar entries using the CCL programming language. Detailed instructions of how to do this are given in chapter on programming, chapter 8.

Also on the main screen there is at least one **graphics window.** This has a **toolbar** consisting of a row of **icons.** All graphical output is displayed in one of the graphics windows. Graphical analysis is discussed in chapter 5. There is an index of OSLO graphics facilities in Appendix 2 at the end of this book.



HELP! *If the graphics window toolbar does not look like the one in the diagram, click on the* **Setup Window/Toolbar** *icon on the left-hand side of the graphics window toolbar, and select* **Standard Tools** *from the menu. Only one of the graphics window icon groups may be displayed at a time, but different graphics windows may have different groups. Up to 30 graphics windows may be created and displayed by the user at any one time. Two more may be generated automatically.*

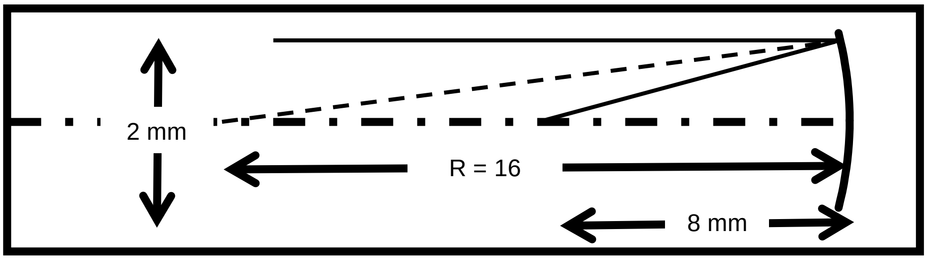
The user may generate icons in any of the graphics toolbars. This is described in chapter 8.

HELP! *If you have trouble finding the text window or the graphics window, then from the* **Window** *menu header select* **Tile Windows.** *Alternatively you can type the command* `tile` *into the command line and then either click on the green tick* ✓ *or press* ↵ **(Enter)** *on the keyboard.*

Spherical mirror example

The remainder of this chapter will consist of instructions on how to specify a concave spherical mirror of radius 16 mm, and then to assess its on-axis performance at apertures of f/4 and f/2.3. Finally its performance at 18° off axis will be assessed, and the stop position and image radius of curvature optimized to give the best performance over the field of view.

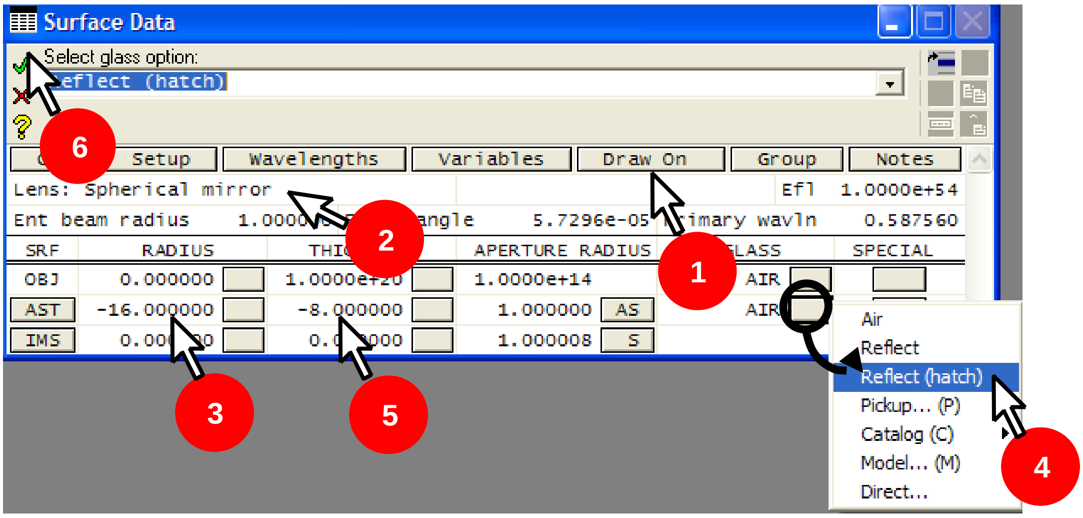
For clarity, each section will be prefaced by a question from a “customer,” given in bold type.



Question: Does a spherical mirror working at f/4 give a “diffraction limited” image at its focus when used with a 2 mm diameter parallel axial beam of green light?

Defining the lens system data

The working conditions of the lens (such as units, paraxial setup data, wavelengths and field points) are defined by entries in the surface data spreadsheet above the double line.



On the surface data spreadsheet:

1. Left-click with the mouse on Draw Off to open the **Autodraw** window The label on the button changes to Draw On while the **Autodraw** window is active.
2. Add the lens identifier (up to 32 characters): **Lens:** `Spherical mirror` Click once on the green tick.

HELP! *If you were to choose a different name for the lens identifier, and the first word of the name happened to be a valid OSLO command words (such as* `spe`*), the name would be* *rejected and the relevant command executed instead. To avoid this, the title might be enclosed in quotation marks: e.g.* **“spe”**.

The default value of **Ent beam radius** is 1.0 mm, the default primary wavelength is 0.58756 µm (the green helium d-line), and the default units are mm, so for this exercise these do not need to be changed. Also at this stage it is only necessary to assess the mirror on axis, so the field angle does not need to be changed from the default value of 1 microradian.

Defining the lens surface data

Turning now to the data below the double line, the first line (labeled **OBJ**) refers to the object space, numbered 0. A parallel beam is the default condition for a new lens. So the **THICKNESS** - that is the object distance - is infinity (in OSLO, that means 10^{20}, written **1.0000e+20** lens units). Nothing has to be changed on this line since in the object space a medium (**GLASS**) of **AIR** is also the default. The object radius (1.0000e+14) is calculated from the field angle by the program, and is not specified by the user.

On the second line for surface 1 (**AST**):

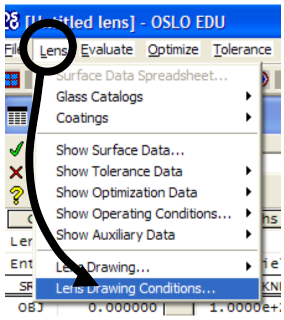
3. Because the aperture is “f/4” the focal length must be 4 times the beam diameter of 2 mm, and the focal length is half the radius of curvature. Change the **RADIUS** to a value of **-16** (mm). Since this is measured from the surface to its center, a negative radius implies a surface concave to the incoming beam.
4. Click on the gray button next to **AIR** under **GLASS** and select **Reflect (hatch)** (or **Reflect** - the only difference being the appearance of the drawing).
5. Change the **THICKNESS** from 0.000000 to: **-8** (mm). This is the separation from surface 1 to surface 2. It is negative because after reflection the light travels in the opposite direction to the local z-axis.
6. Once again, click on the green tick (✓) to confirm the changes.

Note that for surface 1, the **APERTURE RADIUS** (1.000000) has **AS** in the gray box next to it. **A** means that this surface is the aperture stop. **S** means that the size of the surface is governed by a “paraxial solve,” which means that it will be adjusted to accommodate (approximately) both axial and off-axis beams without truncation.

On the third line, which corresponds to the image (**IMS**) a **RADIUS** of 0.0 means that the image is plane. Once again its size is the default - it is adjusted using a “paraxial solve.” The box for the next space (**THICKNESS**) will used for a defocus value, but is zero at present. The box showing the medium after the image (**GLASS**) is of course blank.

There is no need to close the surface data spreadsheet before starting the next section.

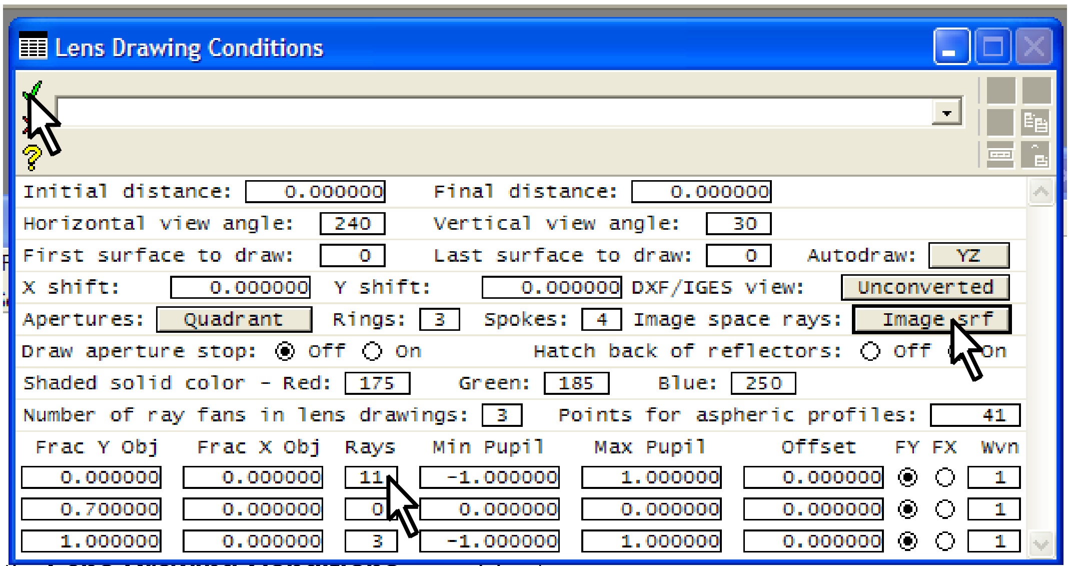
Drawing the lens in the Autodraw window



In the main window:

- Click on the **Lens** menu header to open the menu list shown.
- Select the last item, **Lens Drawing Conditions ...**

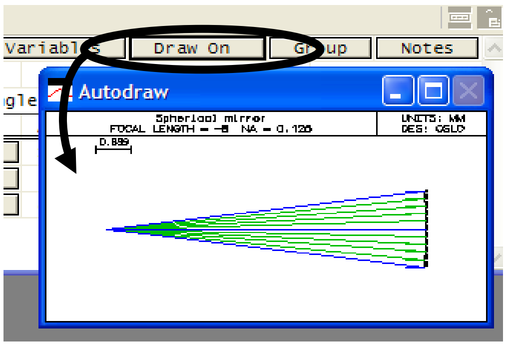
The **Lens Drawing Conditions** spreadsheet will appear. This is the spreadsheet where the overall appearance of lens system drawings is determined.



In the **Lens Drawing Conditions** spreadsheet:

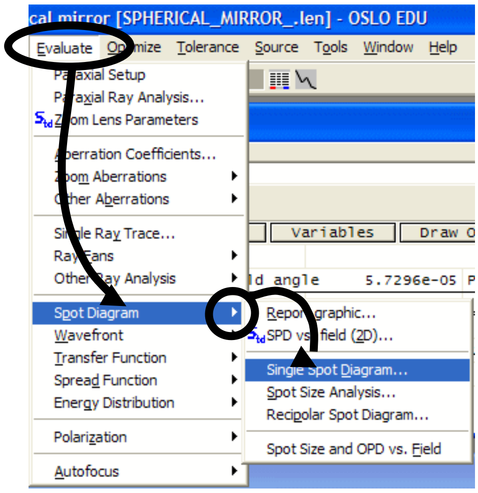
- After **Image space rays:** select **Draw rays to image surface**.
- The table at the bottom determines what rays will be displayed. In the column headed **Rays** type on the first line **11** for the number of rays to be drawn for the first (on axis) field point - for which **Frac Y Obj = 0.00000**. These rays will be drawn with a green pen.
- Leave everything else unchanged, and close with the green tick ✓.

The **Autodraw** window should now have the appearance shown in the diagram, provided the surface data spreadsheet is open.



HELP! *The* **Autodraw** *window may be hidden behind one of the others. If this happens to be the case, from the* **Window** *menu header select* **Tile Windows**

Plotting the on axis spot diagram



A spot diagram is a map of the pattern of rays incident on the image from a single object point, using the “geometrical approximation” which ignores the wave nature of light.

- From the **Evaluate** menu header select: **Spot Diagram** ►**Single spot diagram...**
- In the **Print or plot spot diagram** spreadsheet, click on three radio buttons as shown:

⦿ Plot spot diagram.

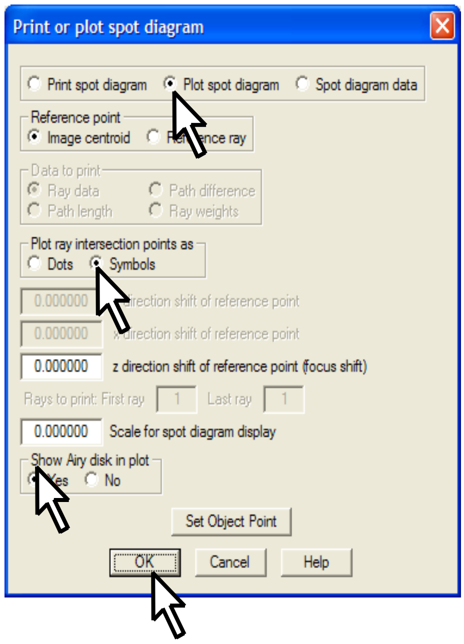
Plot ray intersection points as:

⦿ Symbols

Show Airy disc in plot:

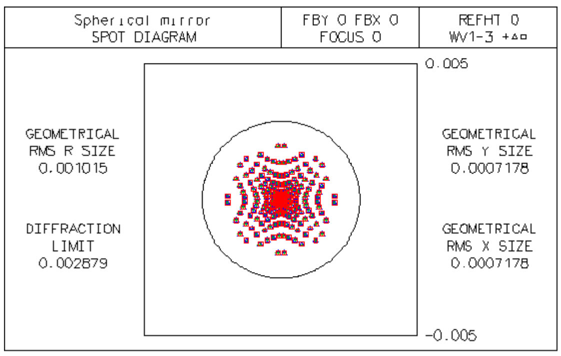
⦿Yes

- Leave the other entries as defaults; the axial (**FBY = 0, FBX = 0**) is the default so there is no need to use the **Set Object Point** button.
- Click on **OK**



The colored symbols in this diagram represent the distribution in the image plane of rays which evenly fill the pupil from a single point on axis. The three colors represent the three default wavelengths. The black circle represents the first minimum of the Airy disc, which is the intensity in the image of a perfect lens of the same aperture, in monochromatic light of the default central wavelength of 0.58756 μm.

The most important aspect of the diagram is that all the rays fall within this circle. This is one of the criteria by which the assertion can be made:



Answer: Yes, the image quality at the focal point is “diffraction limited” - i.e. limited by the wave nature of light and not by aberrations.

HELP! *Once again, if you have trouble finding the graphics window, from the* **Window** *menu header select* **Tile Windows** *or type the command* `tile` *into the command line.*

- Close the surface data spreadsheet by clicking on the green tick ✓.

Listing the lens surface data

- Click on the **Len** header in the text window to list radii, thicknesses, apertures, glass types and surface notes:

```
*LENS DATA
Spherical mirror
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE   NOTE
 OBJ        --          1.0000e+20     1.0000e+14             AIR

 AST    -16.000000      -8.000000       1.000000 AS    REFL_HATCH

 IMS        --             --          8.0000e-06 S
```

- Click on **Rin** to list the indices and thermal expansion coefficients:

```
*REFRACTIVE INDICES
 SRF   GLASS/CATALOG         RN1         RN2         RN3         VNBR        TCE
  0    AIR                1.000000    1.000000    1.000000       --          --
  1    REFL_HATCH         1.000000    1.000000    1.000000       --          --
  2    IMAGE SURFACE
```

- Click on **Ape** to list apertures and any special apertures.

```
*APERTURES
 SRF    TYPE APERTURE RADIUS
  0      SPC   1.0000e+14
  1      CMP     1.000000
  2      CMP   8.0000e-06
```

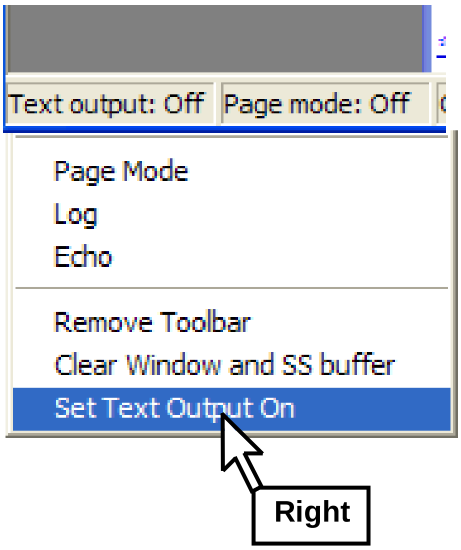
- Click on **Wav** to give the wavelengths and the spectral weighting factors on each.

```
*WAVELENGTHS
CURRENT   WV1/WW1      WV2/WW2      WV3/WW3
   1     0.587560     0.486130     0.656270
         1.000000     1.000000     1.000000
```

- Click on **Pxc** to list the focal length and some of the operating conditions.

```
*PARAXIAL CONSTANTS
   Effective focal length:    -8.000000    Lateral magnification:   -8.0000e-20
   Numerical aperture:         0.125000    Gaussian image height:    8.0000e-06
   Working F-number:           4.000000    Petzval radius:            -8.000000

   Lagrange invariant:     -1.0000e-06
```

HELP! *There are occasions when the text output gets turned off inadvertently. This is most likely to occur if a CCL command is interrupted before it has had time to complete its task. If nothing appears in the text window when text output is expected, look at the first panel on the status bar at the bottom of the main window. If it reads* **Text output: Off**, *right click within the text window, and select the last menu entry:* **Set Text Output On.**

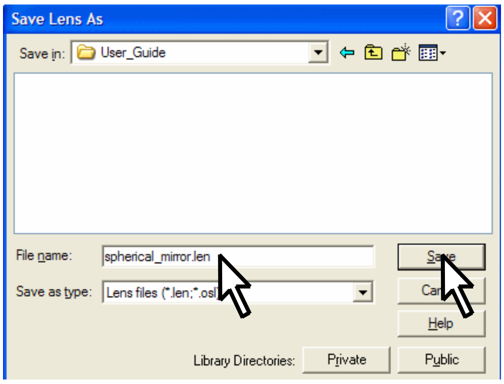


Saving the lens

To create a new folder and save the lens in it:

- From the **File** menu header select **Save Lens as ...**

- Of the two buttons labeled **Library Directories** at the bottom of the **Save Lens As** window, click on **Private**

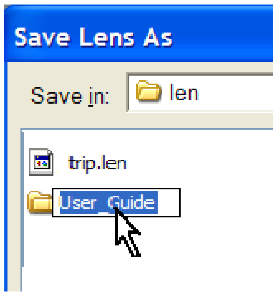


- At the top of the window, click on the icon:

Create new folder

- Type the name for the new folder: `User_Guide` and click on **Open**
- Under **File name** type: `spherical_mirror`
- Click on **Save** to save the lens with the file name `spherical_mirror.len`

Note that OSLO is case insensitive, so this file cannot coexist with another file called, for example, `SPHERICAL_MIRROR.len`



- Close the surface data spreadsheet with the green tick ✓
- The lens will be stored in the private lens directory e.g. **C:\Program Files\OSLO\EDU64\private\len** in the newly created **\User_Guide** subdirectory. The file is in ASCII format and contains the following text:

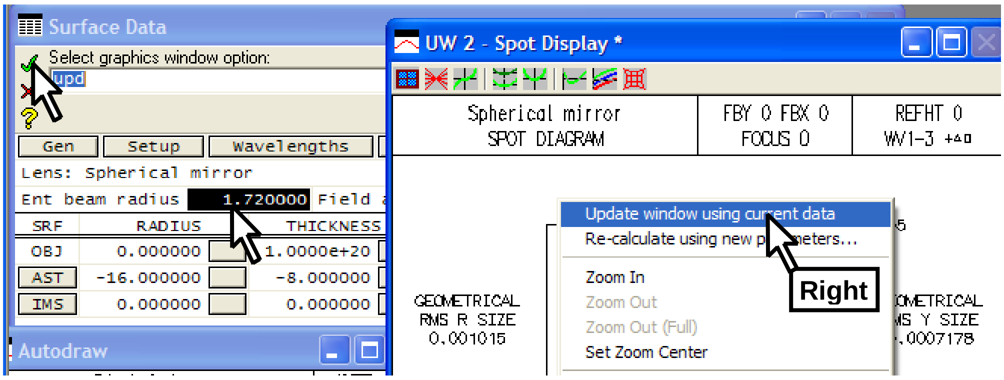
```
// OSLO 6.4 39660     0 16046
LEN NEW "Spherical mirror" -8 2
EBR  1.0
ANG  0.0000572957795
DES  "OSLO"
UNI  1.0
// SRF 0
AIR
TH   1.0e+20
AP  9.9999999995e+13
NXT  // SRF 1
RFH
RD   -16.0
TH   -8.0
NXT  // SRF 2
AIR
WV 0.58756 0.48613 0.65627
WW 1.0 1.0 1.0
END  2
DLRS 3
DLNR  0 11
```

An explanation of these commands will be found in Appendix 1.

Changing the aperture

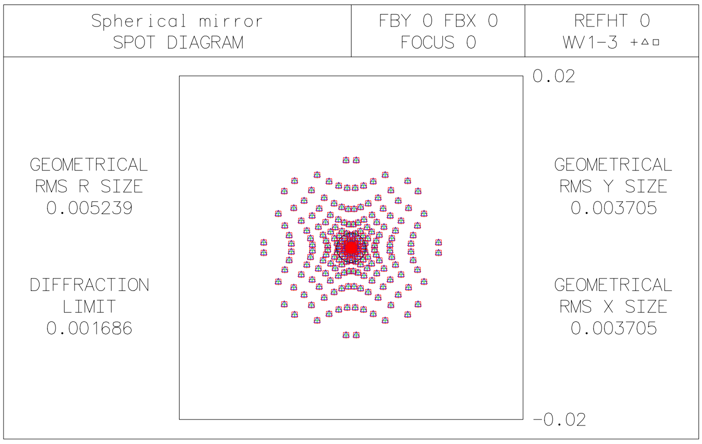
Question: If the aperture of the spherical mirror is increased to 3.44 mm is it still "diffraction limited" at the new aperture?

- In the surface data spreadsheet increase the entrance beam radius from 1 mm to **1.72** mm.
- Confirm with the green tick ✓.



Now recalculate the spot diagram:

- Right-click anywhere inside the graphics window containing the spot diagram plotted previously.
- Select **Update window using current data:** to create the diagram shown at right.



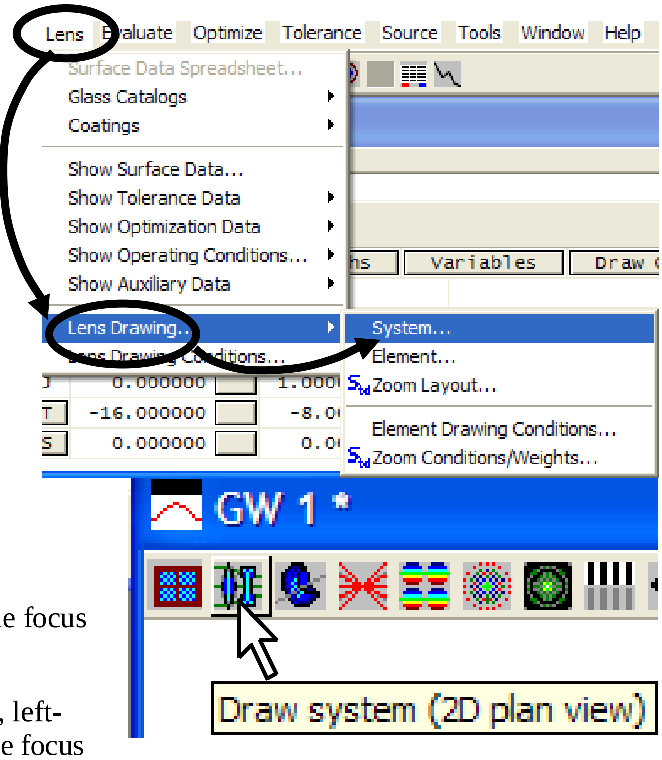
Because the aperture has increased, the spot diagram is bigger (because of greater aberrations) and the Airy disc is smaller (it is inversely proportional to the aperture). Most of the rays therefore now lie outside the Airy disc circle.

Answer: No, it is far from diffraction limited.

Drawing the lens in the graphics window, with "zooming"

To draw the lens system in a graphics window:

- From the **Lens** menu header select **Lens Drawing ...**
  - ▶ **System**
- Accepting all the defaults click on **OK**

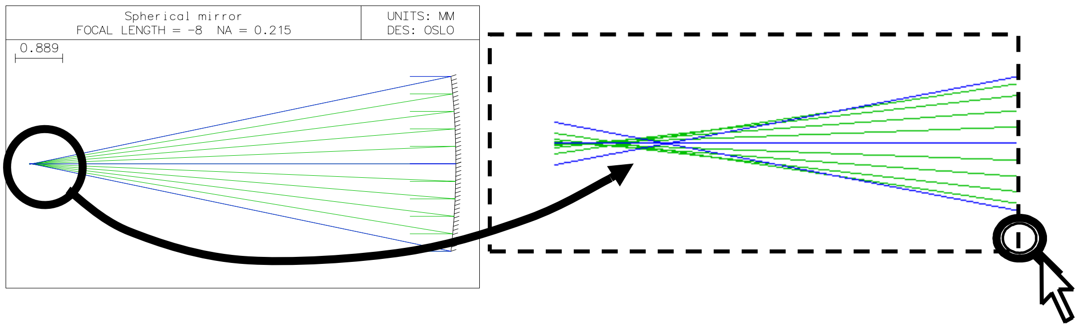


Alternatively,

- Click on the first icon in the graphics window standard toolbar for **Draw system (2D plan view).**
  - Select **Plan View ...**

To view the paths of rays near the focus at a higher magnification:

- On the graphics window, left-click-and-drag around the focus as shown below.
- Left click twice within the graphics window to return to the full frame image.



Note that the zooming action will work on all graphics windows *except* the **Autodraw** window.

Clearly a better focal plane can be chosen, a short distance to the right of the current one.

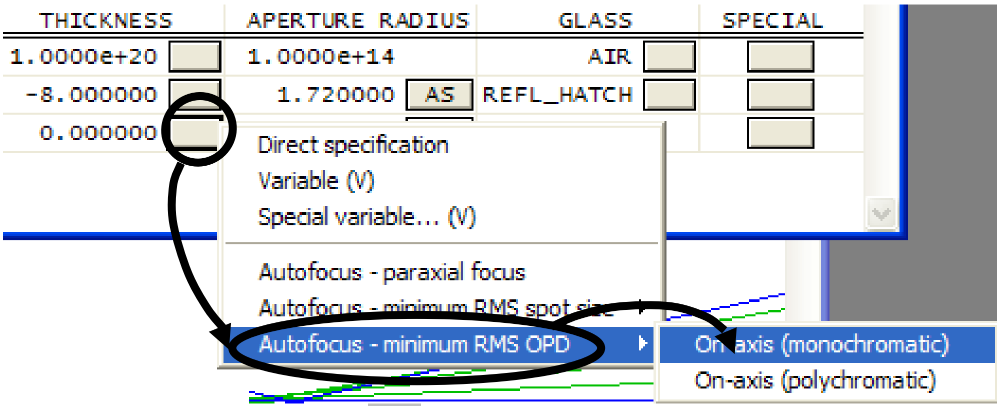
Finding the best focal plane

Question: At this new aperture, where should the focal plane be chosen to give the best image quality for green light on axis?

This can be found most quickly using the “autofocus” facility in the surface data spreadsheet, one of a number of built-in optimization functions.

- Open the surface data spreadsheet.
- Click on the gray button next to the thickness for the image surface (surface **IMS**).
  - Select **Autofocus - minimize RMS OPD ...** ► **On-axis (monochromatic)**

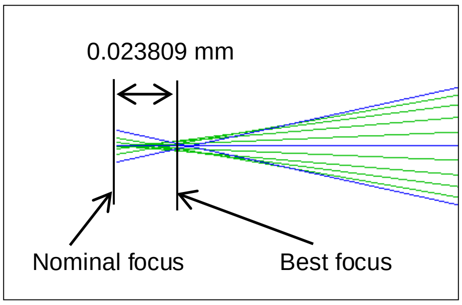
In this context, RMS OPD refers to the root mean square “optical path difference” (or wave aberration). This autofocus action has the effect of finding the focal plane which minimizes the RMS OPD and entering the necessary displacement as the thickness for the image space. The thickness for the space preceding the image space is left unchanged.



Listing the lens data - click on the **Len** header in the text window - gives the extent of defocus needed:

```
*LENS DATA
Spherical mirror f/2.33
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS   SPE   NOTE
 OBJ         --          1.0000e+20    1.0000e+14             AIR

 AST    -16.000000       -8.000000      1.720000 AS    REFL_HATCH

 IMS         --           0.023809      0.005127 S
```

The value listed for the defocus, shown as the thickness at the image plane, is 0.023809 mm. To get the actual distance from the mirror to the image it is necessary to add the defocus value to the nominal distance of -8 mm.



This is the only case in OSLO where an entry in the thickness column of the surface data spreadsheet for a surface affects the axial position of that surface rather than the surface which follows.

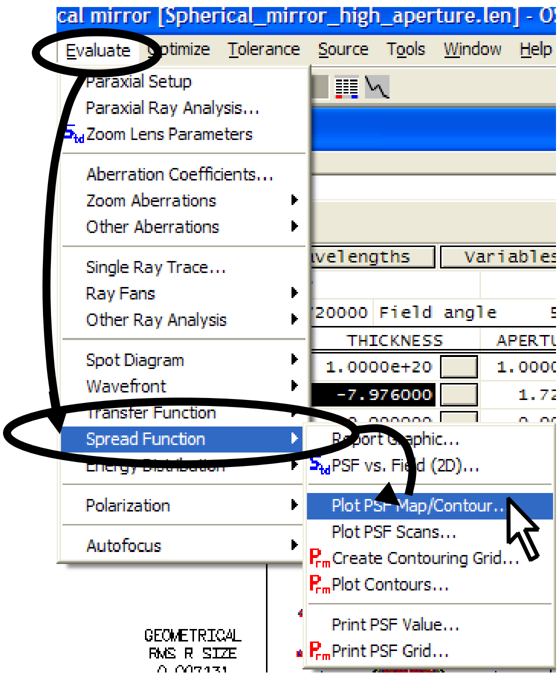
Answer: The best focus at an aperture of f/2.33 is at 7.976 mm from the mirror.

Plotting the on axis point spread function (PSF)

Question: Is the image "diffraction limited" at the new focal plane?

The evaluations carried out hitherto only show approximations to the actual distribution of light in the image of a point source, since a spot diagram takes no account of diffraction.

To plot the true distribution of light in the image of a monochromatic point source, that is to say, the point spread function:

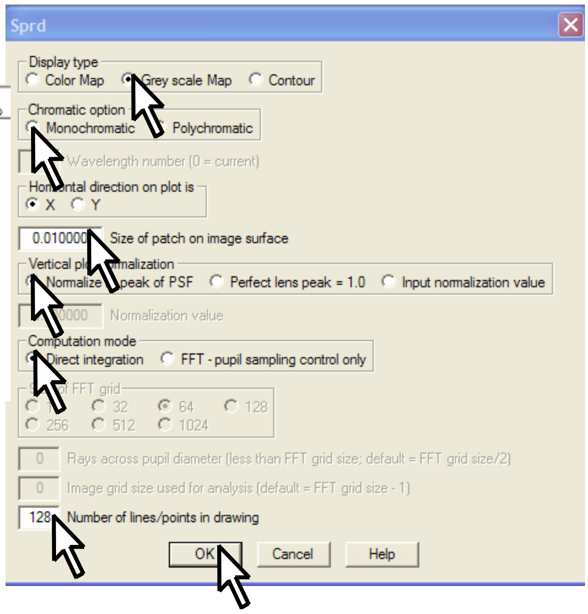


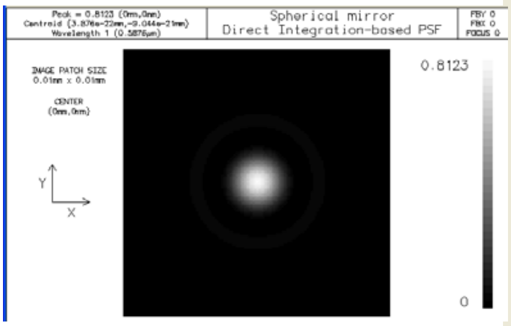
- From the **Evaluate** menu header select:
  Spread Function
  ▶**Plot PSF Map/Contour...**

In the **Sprd** window which opens:

- Click on the radio button
  ⦿ **Gray scale map**
- Click on the radio button
  ⦿ **Monochromatic**
- Type in **0.01** for the
  Size of patch on image surface.
- Click on the radio button:
  ⦿ **Normalize to peak of PSF**
- Click on the radio button:
  ⦿ **Direct integration**
- Type in **128** for
  Number of lines/points in drawing

and click on **OK**

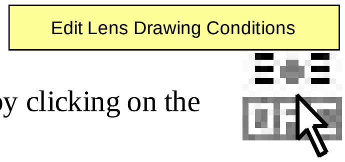




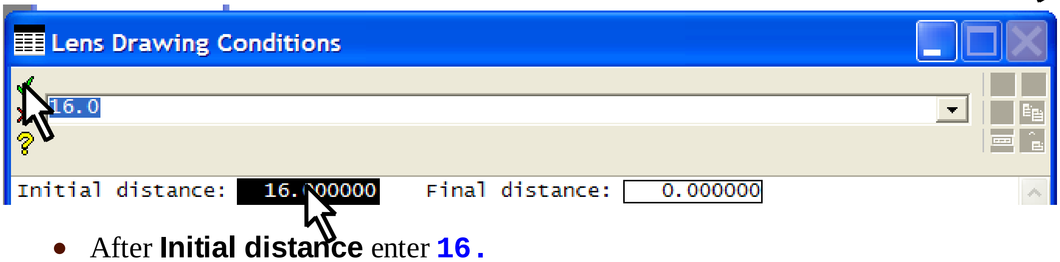
Note that the first bright ring around the central maximum can just be seen. Note also the figure at the top of the scale on the right: **0.8123**. This figure is called the "Strehl ratio," which is the intensity at the central peak of the image of a point source, normalized to that of the Airy diffraction pattern of an ideal lens. The Maréchal criterion states that if the Strehl ratio exceeds 0.8, a lens system may be described as "diffraction limited".

Answer: Yes, the image is diffraction limited on axis at the new focal plane.

Extending the rays in the lens drawing



- Open the **Lens Drawing Conditions** spreadsheet by clicking on the icon in the main window toolbar.

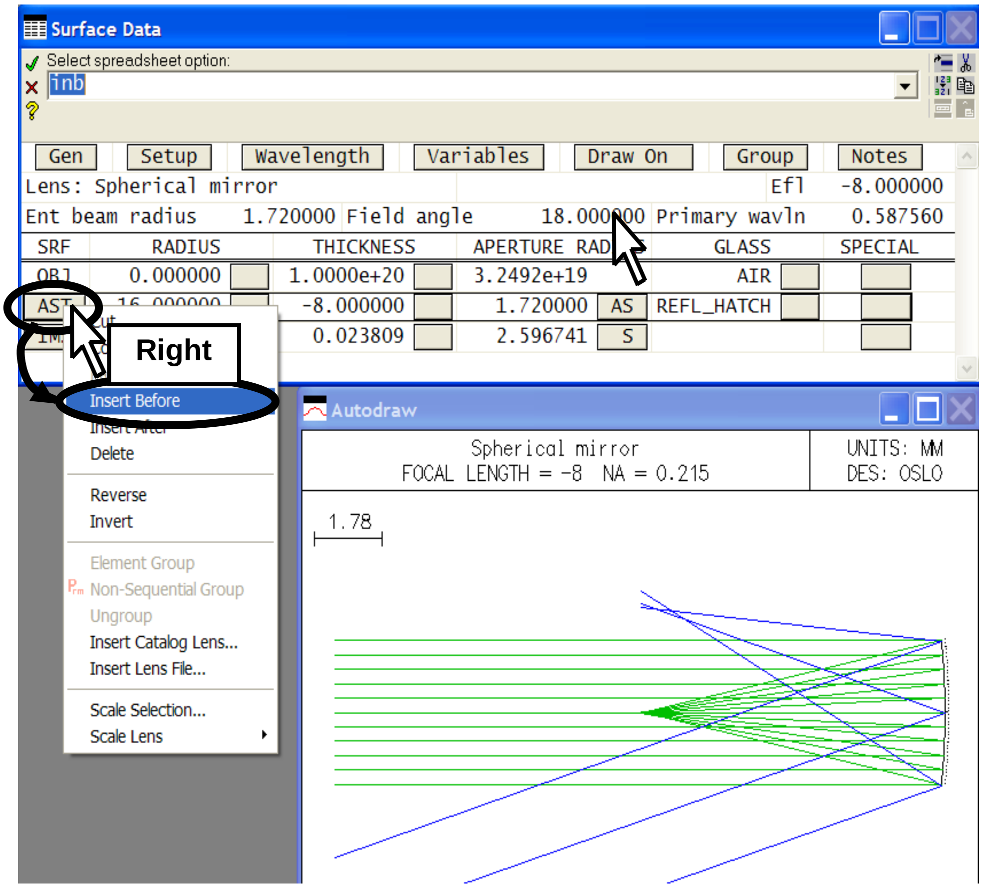


- After **Initial distance** enter **16.**
- Close the spreadsheet with the green tick ✓.

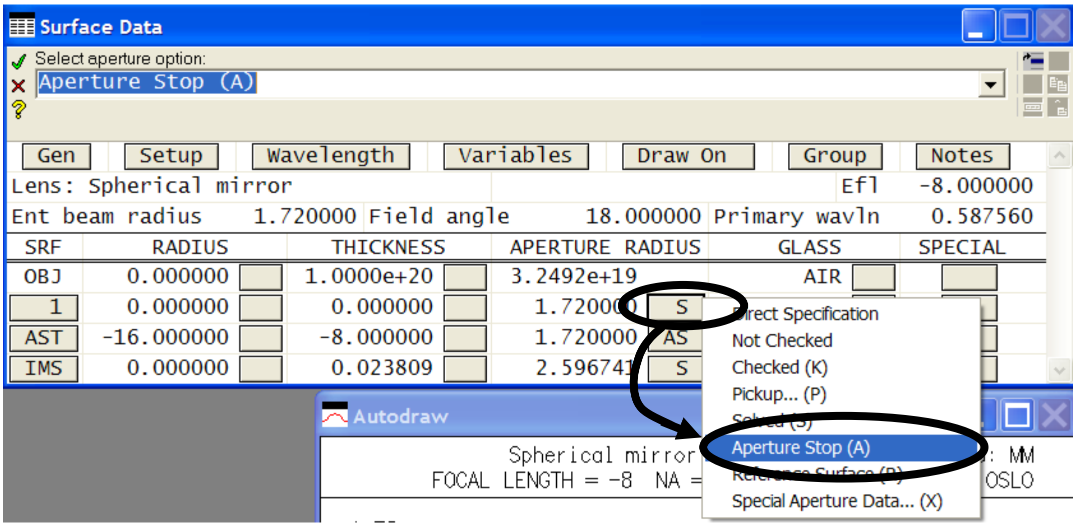
Calculating the off axis optical path difference (OPD)

Question: What is the maximum OPD at full field for a semi-field angle of 18° (total field angle 36°)?

- Open the surface data spreadsheet.
- Enter **18.0** degrees as the (semi-field) **Field angle**
- Left click on the gray **SRF** button for surface **1** (**AST**) to highlight the whole row.
- Right click to bring up the menu of options.
- Select **Insert before** to insert a new surface as surface 1.



- Under **APERTURE RADIUS** for the new surface **1**, click on the gray button.
- Select **Aperture stop (A)**



The aperture stop indication (**AST**) on the gray button under **SRF** will now move to surface 1, which at the moment is in contact with surface 2.

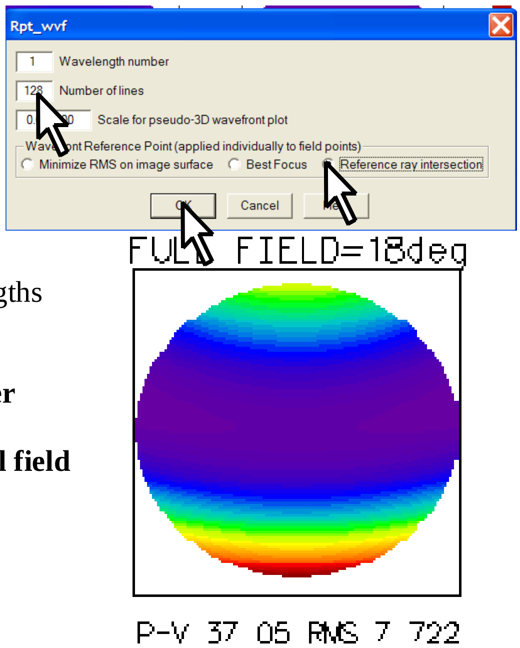
Note that the aberrations of the rays in the off-axis beam (drawn in blue) are so large that they can easily be seen in the lens drawing.

To calculate the optical path difference, or wave aberration, over the whole pupil for three field points (on axis, 0.7 field and full field):

- From the **Evaluate** menu header select: **Wavefront** ► **Report graphic...**

and in the dialog box which opens:

- Enter **128** as the **Number of lines**
- Select ⦿ **Reference ray intersection**
- Click on **OK**



Note the peak-to-valley figure of 37.05 wavelengths under the map for the full field wave aberration.

Answer: The axial performance is better than the standard criterion of a quarter of a wavelength for the diffraction limit, but at full field off axis the maximum OPD is 37 wavelengths.

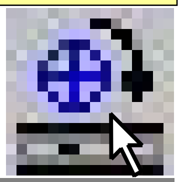
Optimizing

The aperture stop is the limiting aperture of the axial beam. Its longitudinal position determines the beam which is selected to form the off-axis image, and if the field is large, this can have a significant effect on image quality.

Also the image has been assessed only over a plane surface - this is of course the usual convention. For this exercise, however, we will investigate the benefits of allowing the image to become curved.

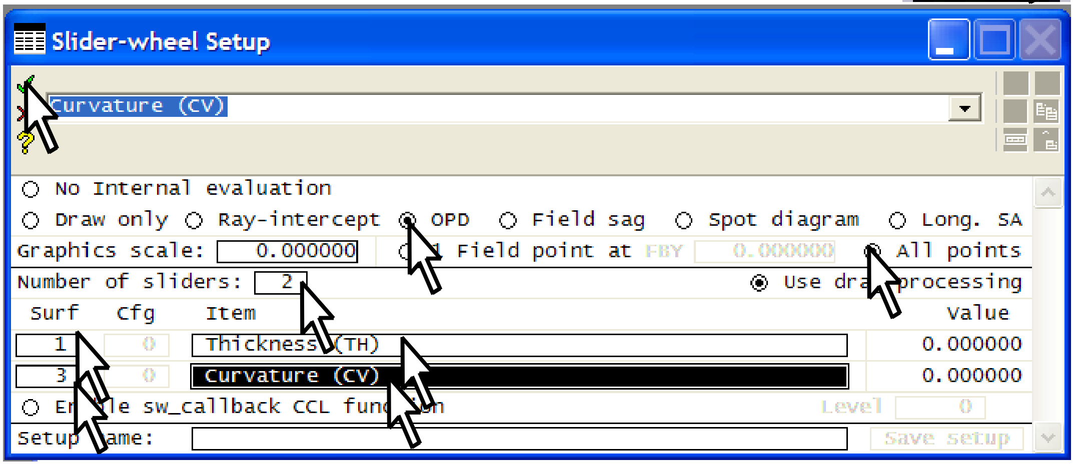
Question: Where should the stop be placed, and what curvature of the image is needed, to obtain the best performance over the whole field?

Open the slider wheel spreadsheet



The answer to this question will demonstrate slider wheel optimization, one of the most useful features of OSLO.

- Close the surface data spreadsheet.
- Open the **Slider-wheel Setup** spreadsheet, by clicking on the icon on the main window header.

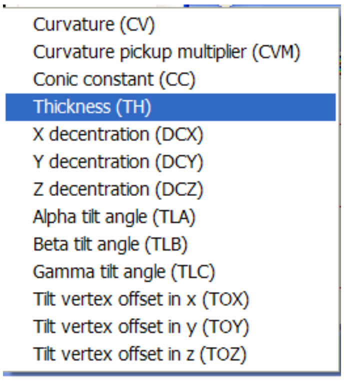


The entries above the line define the contents of the window(s) which will be displayed during slider-wheel optimization.

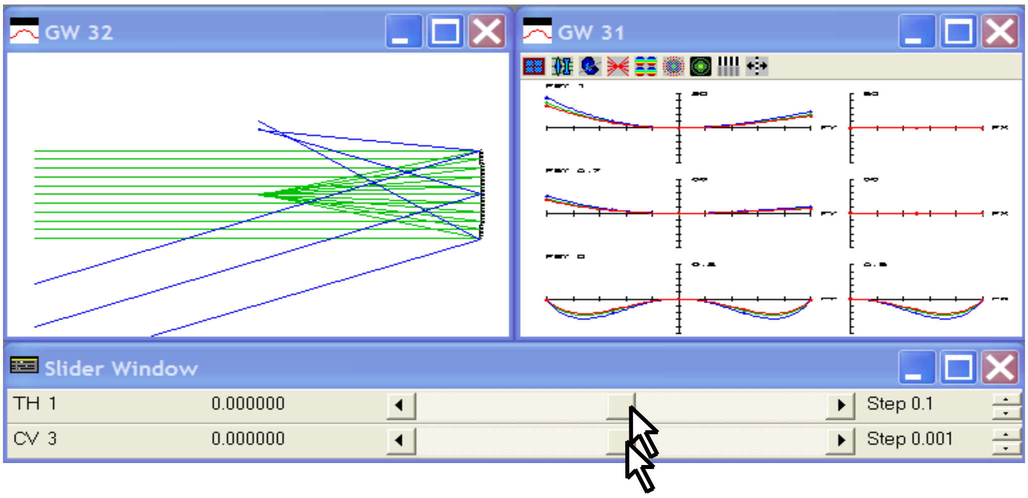
- Select ⦿ **OPD** (optical path difference, another name for wavefront aberration)
- Select ⦿ **All points**

Entries below the line determine which parameters will be adjusted with slider-wheels:

- Leave the default of **2** for the **Number of sliders** (up to 32 can be defined at any one time).
- On the first line, enter **1** under **Surf** and type **th** in the box under **Item.** Alternatively click on the box and select **Thickness (TH)** from the menu of options.
- On the second line, enter **3** under **Surf** and type **cv** under **Item.**
- Click on the green tick ✓ to close the **Slider-wheel Setup** spreadsheet.

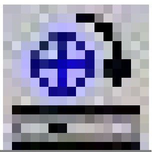


The two graphics window which open, **GW31** and **GW32**, are specific to slider-wheel optimization. The scrollbar at the right of each slider wheel track can be used to adjust the step increment of the slider-wheel motion. Changing the step size also has the effect of centralizing the slider-wheel in the track.

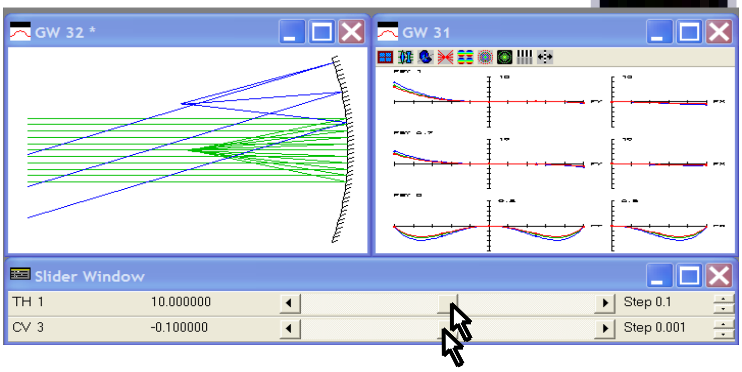


- Watching the lens drawing in **GW 32,** and the plots of the optical path difference in **GW 31**, move the upper slider to the extreme right (**th 1 = 10**) and the lower slider to the extreme left (**cv 3 = -0.1**).

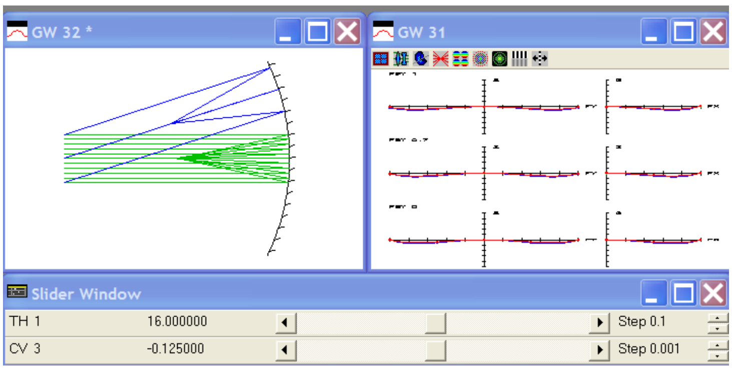
- Once again, open the **Slider-wheel Setup** spreadsheet, by clicking on the icon. However this time just close it again immediately. This has the effect of centralizing the two slider-wheels and re-drawing both windows with different scales.



Although the OPD graphs give no indication of scale, it can be seen that the performance is much improved.



- Repeat the sequence once more until the best result is given. This should be when **TH 1 = 16.0** mm and **CV 3 = -0.125** mm^{-1}



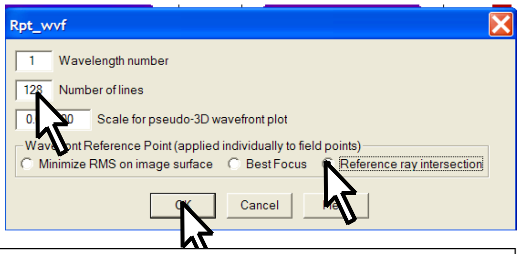
Answer: The aperture stop must be at the centre of curvature of the mirror, and the image surface must be a sphere with its centre at the aperture stop.

Assessing the final design

To evaluate the optical path difference of the new system, once again:

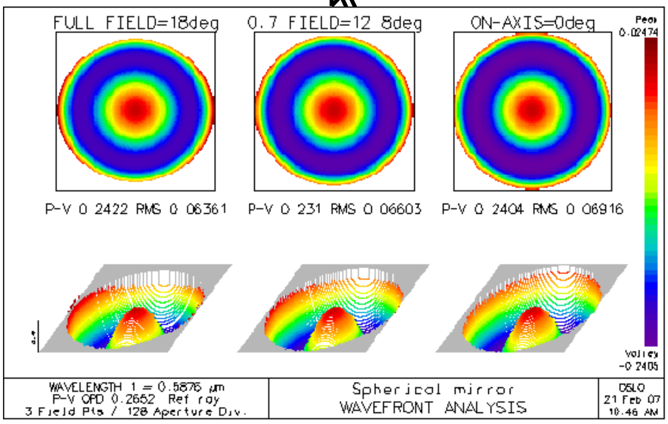
- From the **Evaluate** menu header select: **Wavefront** ▶ **Report graphic...**

and in the dialog box which opens:



- Enter **128** as the **Number of lines**
- Select ◉ **Reference ray intersection**
- Click on **OK**

The peak-to-valley wave aberration at the edge of the field is less than a quarter wavelength, so the lens is diffraction limited over the whole (curved) field.



Listing the data

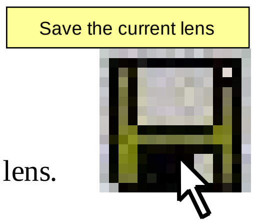
To list the correct prescription of the final design, the image separation needs to be adjusted. In the command line:

- Enter the command: `th 2 -7.976` (note the spaces after `th` and after `2`)

```
SRF  2:
TH     -7.976000
```

- Enter the command: `th 3 0;rtg` to give the final listing (again note the spaces):

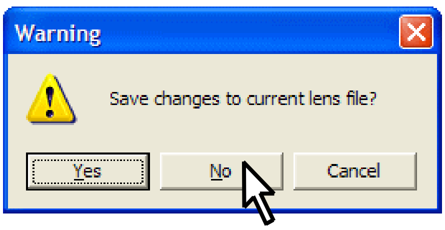
```
SRF  3:
TH           --
*LENS DATA
Spherical mirror
 SRF      RADIUS       THICKNESS   APERTURE RADIUS      GLASS  SPE

 OBJ        --        1.0000e+20    3.2492e+19            AIR

  1         --           --           1.720000 S          AIR

 AST    -16.000000    -7.976000       1.720000 AS    REFL_HATCH

 IMS     -8.000000       --           2.596719 S
```



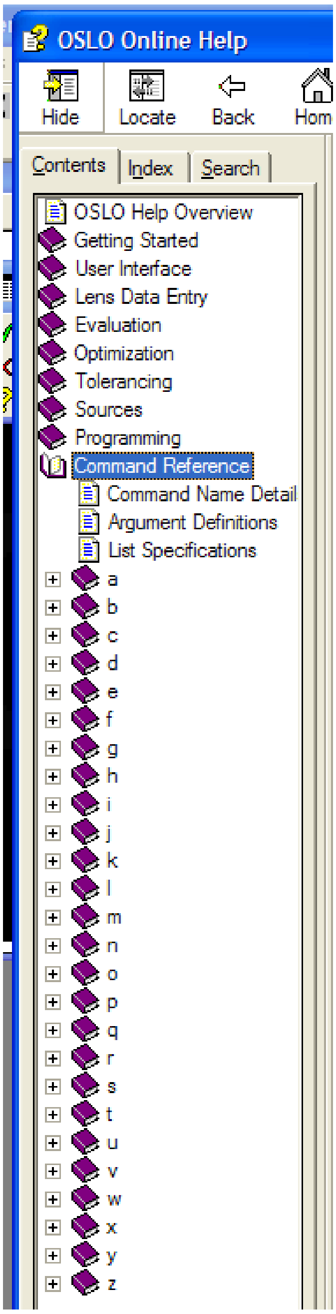
- Click on the save lens icon in the main toolbar to save the lens.

Exiting the program

- From the **File** menu header select **Exit**. If any more changes have been made a message label will give a warning to save the lens, otherwise those changes will be lost.
- Click on **No** and the program terminates.



Conclusion



This introduction shows that OSLO commands can be accessed from the menu headers, from the text window headers, from icons or entered directly into the command line. Commands can also be combined into programs in the languages SCL or CCL, as will be shown in chapter 8.

Command names are important for accessing the documentation in the on-line help. Here are some of the commands that have been used (either explicitly or via the menus and icons) in this chapter:

`file_new`	Opens a new lens file
`uoc drl`	Updates lens drawing conditions
`pls`	Plots spot diagram
`len`	Lists lens data
`save`	Saves lens
`drl`	Draws lens
`auf`	Autofocus
`sprd`	Plots the point spread function
`lse`	Opens the surface data spreadsheet
`rpt_wvf`	Plots wavefront map at 3 field points
`swe`	Opens the slider-wheel spreadsheet
`th`	Changes a thickness
`rtg`	Lists radii/thicknesses/glass types
`exit`	Terminates OSLO.

To obtain a full list of commands:

- From the **Help** menu header select **OSLO Help F1**
- Select the **Contents** tab and click on **Command Reference**. The commands are listed in the alphabetic sub-directories shown here.

Chapter 2 - Configuring OSLO

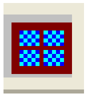
Introduction

Some ways in which the user interface can be adapted will be demonstrated in this section,. It is recommended that these are implemented before proceeding with the remainder of the exercises in this user guide.

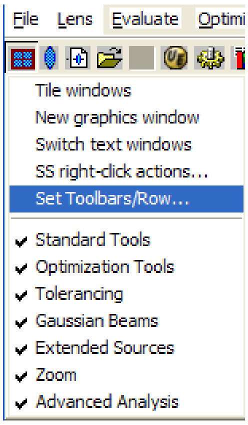
Toolbar menus

This section shows how the toolbars in the main window, the text window, and the graphics window may be populated with icons/tools.

Main window

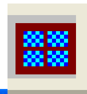


On first use of the program, bring up the full range of icons into the main window toolbar:

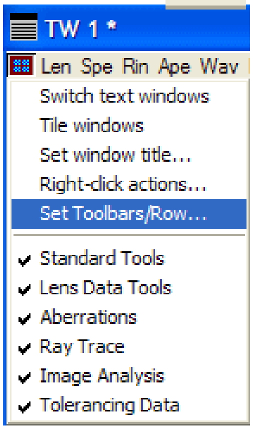


- On the left of the main window toolbar, click on the blue and red window **Setup Window/Toolbar** icon.
- In the drop-down menu which appears click on **Optimization Tools**.
- Repeat for all the other items in the menu (not all the toolbars listed will be available in Light or EDU versions)
- Click on **Set Toolbars/Row...** and, if it is not already 3, enter **3.**

Text window



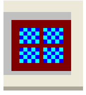
Click on the blue and red window **Setup Window/Toolbar** icon on the left of the text window header.

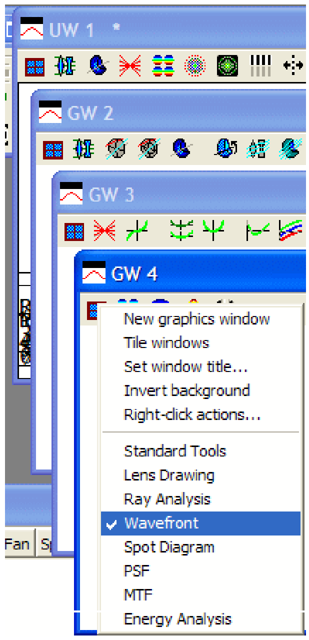


- In the drop-down menu which appears click on **Lens Data Tools**.
- Repeat for all the other items in the menu.
- Click on **Set Toolbars/Row...** and enter **3** for **Maximum number of toolbars on first row.**
- Click on **Switch text windows** to open a second text window, if desired. It will have the same toolbar choices as the first. Only two text windows may be opened at a time.

Graphics window

Each graphics window supports only a single toolbar, but up to 31 additional graphics windows may be opened, each with its own choice of toolbar.



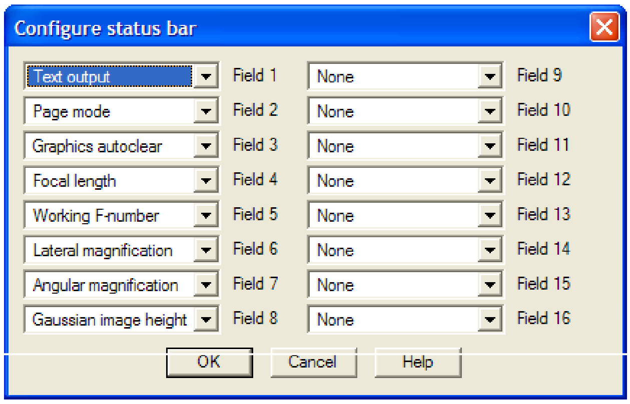


- From the **Window** menu header select: **Graphics►New**
- In the header of the graphics window which opens, click on the **Setup Window/Toolbar** icon.
- Select one of the toolbar options.
- Repeat twice more to open a total of four graphics windows. The current one always has a dark blue bar at the top and an asterisk after the title; the header bars of the others are light blue.

The status bar

The status bar extends across the bottom of the main window for its full width. The following is a suggestion - there are many other possibilities.

- Click twice on the status bar, or from the **Window** menu header select **Status Bar...**
- Leave the parameters for the first three fields unchanged.
- Set the parameters for fields 4 to 8 as follows:



  4. Focal length

  5. Working F-number

  6. Lateral magnification

  7. Angular magnification

  8. Gaussian image height

  For each field, click on the tab on the right hand side of the field, and then select the option from the drop-down menu. This facility is especially useful for keeping an eye on paraxial quantities during optimization.

- Click on **OK** to close the window.

It is not advisable to set more than eight entries as the status bar is limited to 127 characters.

Preferences

Preferences are parameters which control many of the functions of the program operation, regardless of what lens is currently open. Status bar settings and preferences, once set, are preserved after exiting the program. They are stored in a text file called **`oslo.ini`** in the directory **`/private.`** This may be read with a text editor, but it must not be altered.

Preferences may be displayed using the **`show_preference`** command - e.g.

```
shp dsgn
```

or incorporated into print statements - e.g.

```
printf("Current lens directory is %s\n",str_pref(cdir)).
```

- Before starting to define preferences, ensure that the surface data spreadsheet is closed.

Designer name (dsgn)

Several of the graphics windows include a space where the designer's name is listed. The default for new lenses is **OSLO**. To change it:

- From the **File** menu header select **Preferences►Set Preference...**
- From the gray list, select **Designer**
- On the prompt **Enter string preference** type **`[your_name]`** (with a maximum of 10 characters, no spaces) into the command line
- Click on the green tick. ✓

Alternatively, just type **`stp dsgn "[your_name]"`** in the command line and click on the green tick ✓ Note that this will not affect the current lens in storage, but only new lenses created after the change.

ISO10110 drawing settings (adr1, adr2, adr3, edcm)

On ISO 10110 drawings there is a space for three lines of standard information, which normally consists of your company's name and address:

- From the **File** menu header select **Preferences►Set Preference...**
- Select **Address1**
- Type **`[your_company_name]`** (maximum of 36 characters) in the command line under **Enter string preference:**
- Alternatively, in the command line type: **`stp adr1 "your_company_name".`**
- Close with the green tick ✓
- Similarly for **Address2** and **Address3**

  e.g. **`stp adr2 "your_street_address"`**
  `stp adr3 "your_town"`

Commas may be specified instead of decimal points on ISO 10110 drawings:

- From the **File** menu header select **Preferences►Set Preference...**
- Select **Element_drawing_commas**
- Select **On** under **Select Boolean preference:**

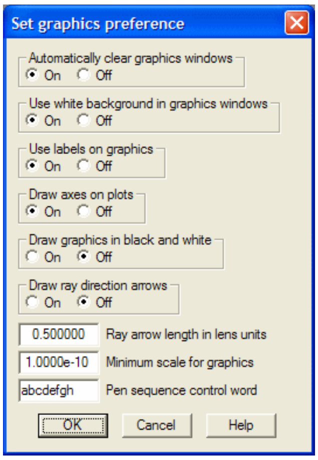
Graphics (gems, gacl, gfwb, glab, grax, gfbw, drra, pens)

Many of the preferences control the appearance of graphics output. For example, when cutting and pasting graphics into Windows, the scale is generally too big for convenience. A better scale is given if the **gems** preference is set to **On**:

- From the **File** menu header select **Preferences►Set Preference...**
- Select **Graphics_emf_sizing**
- Select **On** under **Select boolean preference:**

Several other graphics preferences are collected together for easy access:

- From the **File** menu header select **Preferences ► Preference groups... ►Graphics**
- Modify the entries in the popup box shown in the illustration as required.
- Click on **OK.**



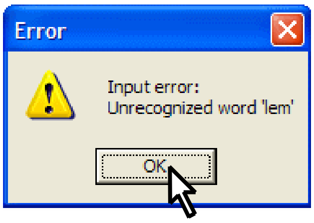
Graphics alternate mode (gfam)

If the aspect ratio of exported graphics is reversed (landscape <-> portrait) then look to see if **gfam on** (**Graphics_alternate_mode On**) has inadvertently been set. If so:

- Enter the command: `stp gfam off`
- Close with the green tick ✓

No error boxes (noeb)

Whenever an error message box appears, it needs to be cleared immediately by clicking on **OK**. This can be a problem on occasions, such as during slider-wheel optimization.

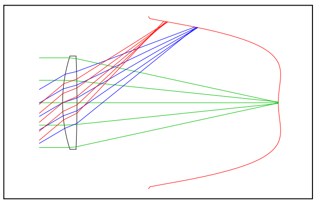


It is possible for the user to suppress these error boxes permanently. If desired:

- From the **File** menu header select **Preferences►Set Preference...**
- Select **No_error_boxes**
- Under **Select boolean preference:** select **On**

Tangent check (tanc on)

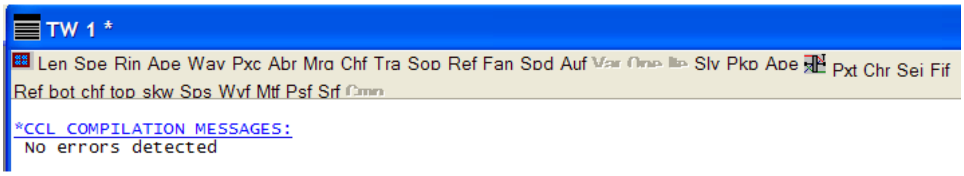
- Enter the command `tanc on` in the command line. This will turn on the facility which permits rays to be drawn to highly aspheric surfaces, such as the one illustrated here.
- Close with the green tick ✓

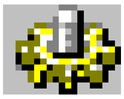


Compile CCL

To avoid potential problems, it is a good idea to compile all CCL files before starting to use the program for serious work. To do this:

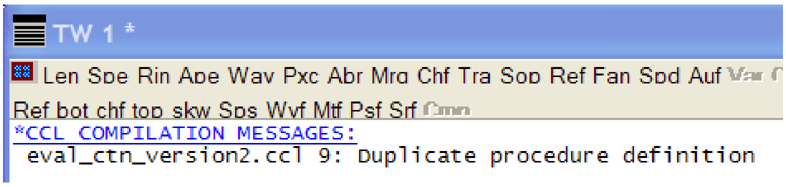
- From the **Tools** menu header select **Compile CCL ...**
- In response to **Select compile access:** choose **`Public.`**
- In response to **Select compile option:** choose **`All`.**
- In response to **Enter ccl opts:** leave the default entry unchanged - e.g.:
  `-D _OSLO_EDU_ -D _OSLO_LIGHT_ -D OPENGL_GRAPHICS`
- Close with the green tick ✓
- Check that the public CCL directory has compiled without error.





- Repeat for the **`Private`** directory, or (***not for users of OSLO EDU version***) click on the icon to “Compile all private CCL”.
  - Once again confirm that the **No errors detected** message has appeared in the current text window.

If an error message is given, then it will be necessary to correct, suppress or delete the file whose name is shown. For example, the error message:



indicates the error occurs on line 9 of the file **eval_ctn_Version2.ccl** in the **private/ccl** directory. Further details are given in chapter 8.

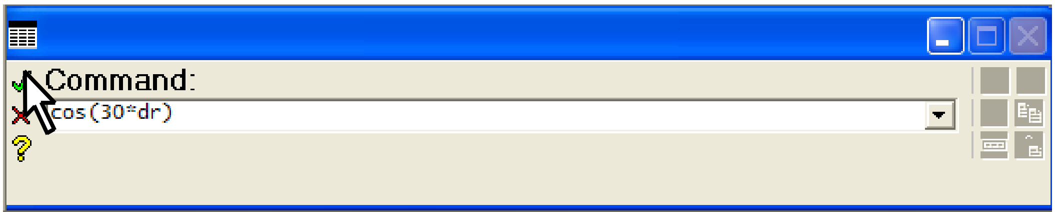
Chapter 3 - The command line

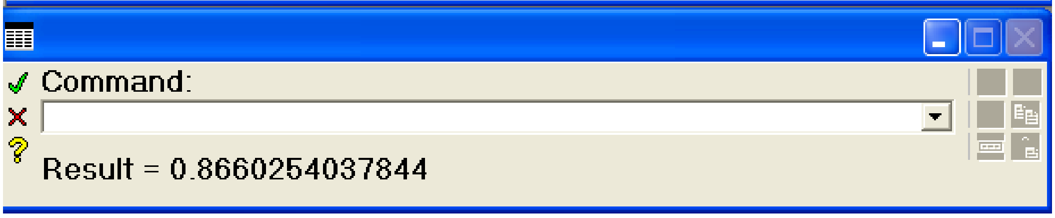
Arithmetic calculations

Simple arithmetic expressions can be evaluated with the result given in the message bar.

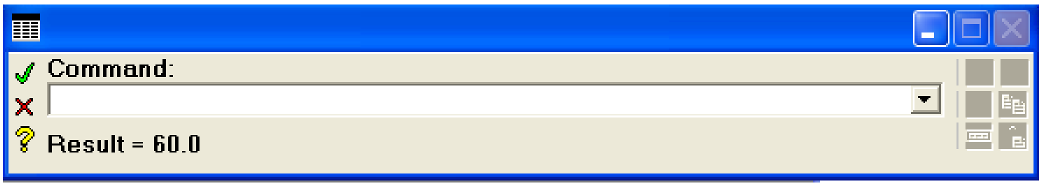
- If the surface data spreadsheet is open, close it by clicking on the green tick ✓.

- Type **cos(30*dr)** and close with **Enter** or the green tick ✓





- Enter **atan2(sqrt(3),1)/dr**



The following table gives all the arithmetical functions available in OSLO EDU:

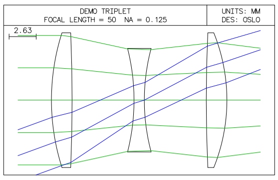
Mathematical:	**pow** (power), **exp, log, log10, sqrt, j0, j1** (Bessel functions)
Trigonometry (all angles are in radians):	
	sin, cos, tan, asin, acos, atan2
Rounding and limits:	**fabs, rint, r2int, round, min, max, floor, ceil**
Random numbers:	**rand** (uniform), **grand** (Gaussian with zero mean)

OSLO commands

The main purpose of the command line is to execute OSLO commands.

- Enter **file_open** and close with the green tick ✓

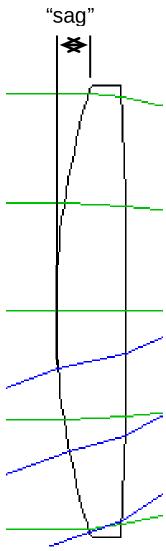
- If the message **Save changes to current lens file?** appears, click on **No**.



- In the **Open lens file** window which opens, under **Library directories** at the bottom, click on **Private**.
- Click on `trip.len`
- Click on **Open**
- If the surface data spreadsheet opens, close it with the green tick ✓.

Multiple commands are stacked with semicolons. For example, if we require to calculate the "sag" of the first surface of the triplet (that is, the distance measured along the axis from the plane through the axial point to the plane through the edge of the clear aperture):

- Enter `rtg 1 1;sag 1 6.5`




```
*LENS DATA
DEMO TRIPLET
 SRF      RADIUS       THICKNESS   APERTURE RADIUS      GLASS SPE NOTE

  1     21.250000 V    2.000000      6.500000 K          SK16 C

*SURFACE SAG AND SURFACE NORMAL
 SURFACE 1
     Y           X          Z (SAG)      NVL        NVK         NVM
   6.500000     --        1.018527   -0.305882     --         0.952069
```

Commands can also be issued in a way that initiates a dialog for subsequent parameters:

- Enter `sag ?`
- In the command window, in reply to the prompt **Enter surface number:** enter `1`
- In reply to the prompt **Enter y:** enter `6.5`
- In reply to **Enter x:** leave the default value `0`
- Close with the green tick ✓

```
*SURFACE SAG AND SURFACE NORMAL
 SURFACE 1
     Y           X          Z (SAG)      NVL        NVK         NVM
   6.500000     --        1.018527   -0.305882     --         0.952069
```

Assigning values to predefined variables

Values can be allocated, using the command line, to predefined variables. Predefined variables are `a ... h, o ... z` (real) `i ... n` and `ii ... nn` (integer). Also pre-defined are seven real arrays with indices 0 - 1999, `ua[] ... za []` and three string arrays of 256 characters `astr, bstr, cstr`. There are also two predefined constants, `dr` (degrees to radians conversion factor), `on` (=1), `off`(=0) and `pi`. All are case-insensitive.

Allocations remain until OSLO is closed and restarted.

For example we can calculate the z ("sag") value listed above:

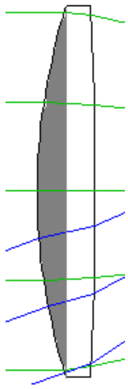
- Enter `r=21.25;y=6.5;z=r-r*cos(asin(y/r))`

- Enter **z**.

```
Result = 1.0185269938148
```

Here the value of z which appears in the message area is the "sag" of the previous example.

Take care if you use **c, f, o, r** or **v** as they are also OSLO command words. **pi** is π, but it is also an OSLO command. So do not enter **pi** on its own, but rather include it in an arithmetic expression.



- Enter: **+pi**

```
Result = 3.1415926535898
```

Take care when arithmetical calculations are carried out while any spreadsheet is open. The results of calculations will, if valid, be used as the contents of the cell which is currently highlighted.

Printing

Results of printing appear in the current text window:

- Enter: **prt At height y sag is z**

```
At height    6.500000 sag is    1.018527
```

For more formal presentation, printed output can be formatted. This command uses the formatted print command **printf** to print the volume of the "cap" enclosed by surface 1.

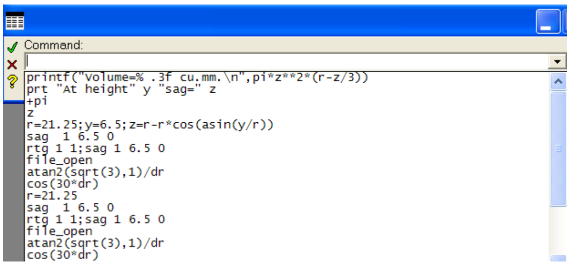
- Enter: **aprintf("Volume=% .3f cu.mm.\n",pi*z**2*(r-z/3))**

```
Volume= 68.149 cu.mm.
```

The first argument is a format string. In it, **% .3f** is a format specification for the double precision numeric value; the space after the **%** reserves a space for a minus sign (if any), **3** gives 3 places after the decimal point and **f** is the conversion character for floating point format. Other characters in a format string are printed unmodified, until the final **\n** which outputs a new line.

The history button

Previous commands can be called up, for repeating a command, or correcting it.



- Click on the history button at the end of the command line.
- Alternatively, press **Shift-F4.** This is known in the documentation as a keyboard shortcut; some others are listed below.
- Enter: **prh** to list the last 40 entries in the history buffer.

Keyboard shortcuts

F1	Open the online help

Ctrl+N	Open a new lens
Ctrl+O	Open an existing lens
Ctrl+S	Save the lens in its current file

In the command line,

Ctrl+X	Cut selected text
Ctrl+C	Copy selected text
Ctrl+V	Paste selected text
Shift+F4	Show the history buffer
Ctrl+PgUp	Scroll through the history (**Ctrl+PgDn** to scroll back)

In the text editor,

Ctrl+E	Execute the selected text
Ctrl+G	Go to the indicated line number
Ctrl+Z	Undo the last edit
Alt+F3	Find text (**F3** to find again)
Ctrl+R	Replace text (**Ctrl-T** to replace again)

In a spreadsheet,

Shift-spacebar	Insert a new line before the current line

The message area

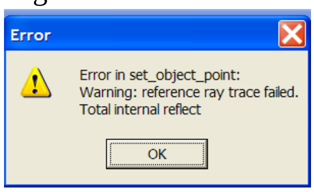
The message area under the command line can be used for formatted output. For example to display a string preference:

- Enter:

```
message("Private dir: %s",str_pref(prid))
```

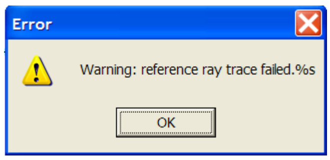
```
Private dir: C:\Program Files\OSLO\Prm64\private
```

The message area is where error messages can be printed. The message command also converts error numbers to strings:



- Enter: `sop 9 0 0`
- Click on **OK** in the error box.
- Enter: `errno`

```
Result = -3152
```



- Different versions of \OSLO have different error numbers. To decode an error number, enter: `message errno` Again, click on **OK** in the error box before proceeding.

Executing CCL command sequences

Valid CCL command sequences which use the pre-defined variables listed above, can be executed within the command line. The total length of the command string must not exceed 255 characters.

- Enter:

```
prt lid;for(i=0;i<=ims;i++)prt cv[i] th[i] rn[i][1]
```

with the result:

```
DEMO TRIPLET
      --       1.0000e+20    1.000000
   0.047059     2.000000     1.620410
  -0.006303     6.000000     1.000000
  -0.049383     1.000000     1.616592
   0.051813     6.000000     1.000000
   0.007080     2.000000     1.620410
  -0.057854    42.950000     1.000000
      --          --         1.000000
```

Here the count variable, **i**, is a pre-defined integer.

The system data variables **lid** (the lens identifier), **cv[i]** (the surface curvature, that is, the reciprocal of the radius), **th[i]** (the separation from surface i to surface i+1) and **rn[i][1]** (the refractive index in the space after surface i at the first wavelength) are all examples of system data variables which can either be printed, or used in arithmetic expressions or CCL programs. A list of such variables is given in the next section.

A system data variable such as **th** cannot, however, be changed by a simple variable assignment statement such as **th[3]=2.0.** An attempt to do this will give the error message:

```
Input error
Protected variable 'th' may not be changed
```

Rather, it must be changed using the dedicated command which has the same name as the variable. For example:

- Enter **th 3 1.05;rtg**

A new image surface may also be defined temporarily in this way:

- Enter **ims 3;rtg**

The remaining surfaces are unaffected, but they will be lost unless the lens is restored before the lens is saved again:

- Enter **ims 7;rtg**

Other commands can be used to change the lens - e.g. the 10th system note, used as a label in the public lens database:

- Enter **sno10 TRIPLET;opc sno**

```
*CONDITIONS: SYSTEM NOTES
10: TRIPLET
```

A list of lens update commands is given in Appendix 1.

Alphabetic list of system data variables

The following is a partial list of the system data variables. To obtain a complete list of all variables exported from OSLO:

- From the **Help** menu header select **OSLO Help F1**
- Under the **Contents** tab select **Programming►Accessing Data ►CCL Global Data**

aac	special aperture action
aan	special aperture angle
ad	aspheric coefficient in r^4
ae	aspheric coefficient in r^6
af	aspheric coefficient in r^8
afo	afocal flag
ag	aspheric coefficient in r^{10}
agn	special aperture group
amo	aberration mode
ang	field angle
ap	apertures
apchk	aperture checking flag
appksn	aperture pickup surface
apspec	aperture spec: ebr, nao, etc.
aptyp	aperture type
as0,as1..	aspheric surf coefficients
asi	alternate surf intersection flag
asp	aspheric surf type
ast	aperture stop surf
atp	special aperture type
avx1	special ap. x vertex 1
avx2	special ap. x vertex 2
avx3	special ap. x vertex 3
avx4	special ap. x vertex 4
avy1	special ap. y vertex 1
avy2	special ap. y vertex 2
avy3	special ap. y vertex 3
avy4	special ap. y vertex 4
ax1	special ap. ax1
ax2	special ap. ax2
ay1	special ap. ay1
ay2	special ap. ay2
bcr	use base coord. for coord
ben	tilt and bend flag
caa	component aper alpha tilt tol
cab	component aper beta tilt tol
cc	conic constant
cca	component coc alpha tilt tol
ccb	component coc beta tilt tol
cct	conic constant tol
cdx	component x-decenter tol
cdy	component y-decenter tol
cns	cone slope
curwav	current wv number (base 1)
cv	curvature
cvdat	curvature solve/pickup datum
cvmult	curvature pickup datum
cvpksn	curvature pickup surf
cvtyp	curvature type
cvx	toric curvature
dct	decenter tol
dcx	x decentration (local)
dcy	y decentration (local)
dcz	z decentration
des	designer name
df	diffractive surf coefficients
dfcsn	diffractive surf pickup
doe	diffractive surf type
dor	diffraction order
drw	surf drawing option
dt	decenter-tilt order flag
dth	grin step size
dwv	design wv (diffractive surf)
dxt	x-decenter tol
dzt	axial surf shift tol
ebr	entrance beam radius
errno	message nbr for last error
evza	image evaluation coord. system
fcc	Fresnel surf substrate conic
fcv	Fresnel surf substrate curvature
fldspec	field spec: obh, ang, etc.
fno	image space working f-number
frn	Fresnel surf flag
gc	global coord. ref. surf number
gcs	global coord. reference surf
gdt	gradient index medium type
gih	Gaussian image height
glpksn	glass pickup surf
gltyp	glass type
gmz	gradium blank thickness
gnz	gradium coefficient
gor	grating order
goz	gradium offset into blank
gra	gradium coefficient
grb	gradium coefficient
grc	gradium coefficient
grd	gradium coefficient
grpcode	group code
grptype	group type
gsp	grating spacing
gwv	gradium dispersion data ref.
hor	hologram diffraction order
hv1	hologram obj. real/virtual
hv2	hologram ref. real/virtual

hwv	hologram construction wv
hx1	hologram object x coord.
hx2	hologram reference x coord.
hy1	hologram object y coord.
hy2	hologram reference y coord.
hz1	hologram object z coord.
hz2	hologram reference z coord.
ims	image surf number
ims_1	image surf number minus one
irt	irregularity tol
ldp	pen for lens drawings
lensym	lens symmetry flag
lid	lens identifier
nao	object space numerical ap.
nap	image space numerical ap.
nr1	grin coefficient in r^2
nr2	grin coefficient in r^4
nr3	grin coefficient in z^6
nr4	grin coefficient in z^8
numsap	number of special apertures
numw	number of wavelengths
nz1	grin coefficient in z
nz2	grin coefficient in z^2
nz3	grin coefficient in z^3
nz4	grin coefficient in z^4
obh	object height
pfl	perfect lens focal length
pfm	perfect lens magnification
pre	system pressure (atm)
puk	image space axial ray slope
rco	coord. return surf number
rd	radius of curvature
rdt	radius tolerance
rdx	toric radius of curvature
rfs	reference surf
rn	refractive indices
rnt	refractive index tol
rod	extruded surf spec
rotsym	rotational symmetry flag
rtf	radius from test glass file
sasd	source astigmatic distance
sh	radial spline height
ska	Sellmeier gradium coefficient
skb	Sellmeier gradium coefficient
skc	Sellmeier gradium coefficient
sla	Sellmeier gradium coefficient
slb	Sellmeier gradium coefficient
slc	Sellmeier gradium coefficient
spl	no. of radial spline surf zone
splpts	number of spline points
spt	spherical form tol
srftyp	surf type
ss	radial spline slope
tat	tla tilt tol
tbt	tlb tilt tol
tce	thermal coefft of expansion
tct	tlc tilt tol
tem	system temperature (deg C)
th	thickness
thdat	thickness solve/pickup datum
thmult	thickness pickup datum
thpksn1	thickness pickup surf
thpksn2	thickness pickup surf
tht	thickness tol
thtyp	thickness type
tir	total internal reflection flag
tla	tilt about (local) -x axis (degs)
tlb	tilt about (local) -y axis (degs)
tlc	tilt about (local) +z axis (degs)
tlt	tilt tolerance
toric	toric type
tox	offset of tilt vertex in x
toy	offset of tilt vertex in y
toz	offset of tilt vertex in z
trr_fbx	fractional x object coord
trr_fby	fractional y object coord.
trr_fbz	fractional z object coord.
trr_fds	field point data
trr_fpt	field point number
trr_fxrf	reference surf x coord.
trr_fyrf	reference surf y coord.
ttun	tilt tolerance units
twl	tol fringe wavelength
txyc	couple x to y tols
uni	number of mm in current units
varnbr	next variable number
vnt	Abbe V-number tol
wav	current wavelength number
wv	wavelengths
ww	wavelength weights
zr	Zernike phase surf coefficients
zrt	Zernike srf reference ray trace

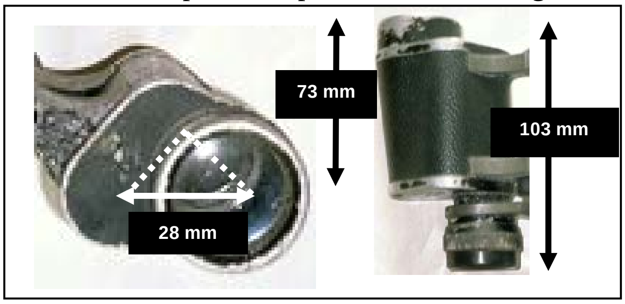
- Also in the online **Help** facility, under the **Contents** tab select **Programming ► Accessing Data ►Other Data** to find the definitions of the following read-only variables:

beg_selection	cfg	current_pen	cursnbr	end_selection
fptnbr	gfx_window	glass_name	lensym	maxcfg
nbr_pens	numw	oprnbr	raynbr	sdsnbr
srfssopen	ssb	surface_note	system_note	txt_window
varnbr	wav			

Chapter 4 - Lens data entry

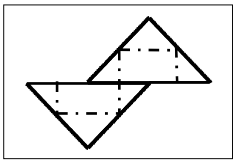
8 x 30 binoculars: Specification

The task which will be used to demonstrate lens data input is the problem of modeling the binoculars shown in the photographs, with 8x magnification, a 30 mm diameter entrance pupil, and a field of view of 6°. Measurements give an overall length from the front of the objective to the back of the eyepiece of 103 mm. The distance from the front objective to the eyepiece mounting plate is 73 mm, and the offset between the optical axis of the objective and the optical axis of the eyepiece is 28 mm.

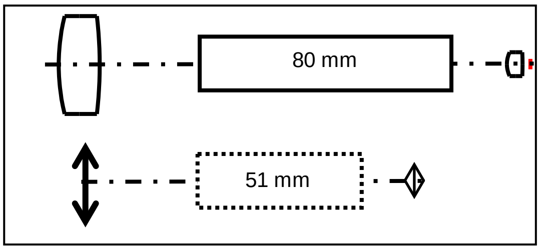


Calculations

First of all we will calculate the sizes of the Porro prisms. Since the offset between the two optical axes is 28 mm, the path perpendicular to the axis of the binoculars must be 20mm in each prism. The total glass pass in each prism must therefore be 40mm, and the total glass path in the two prisms (shown here in an opened-out-view) 80 mm.



The glass which is most commonly used for prisms in the better quality binoculars is Schott BaK4, which has a refractive index of 1.57. The prism path length of 80 mm will then have an “air equivalent” path length of 80/1.57 = 51 mm. This needs to be added to the physical length (103 mm) to give a total air equivalent optical path from back to front of 154 mm. Now, making an allowance of 19 mm for the finite thicknesses of both eyepiece and objective gives a path between the principal planes, or equivalent thin lenses, of 135 mm. So, to obtain the desired magnification of x8, the focal lengths required are 120 mm for the objective and 15 mm for the eyepiece.



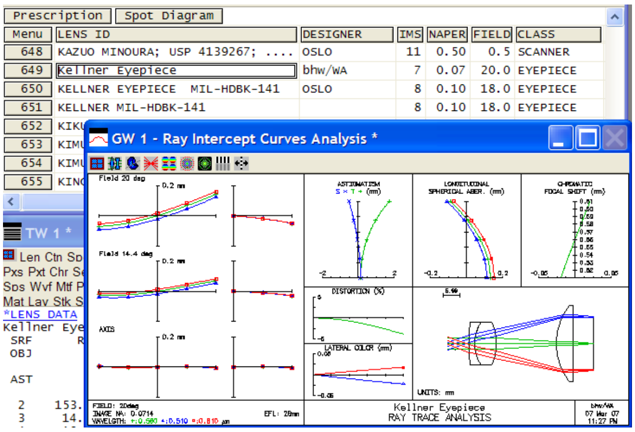
Choosing an eyepiece

The eyepiece in most common use in prismatic binoculars is the Kellner. This consists of a plano-convex single element lens, with a cemented doublet near the eye. An eyepiece suitable for this application can be found in the book “Optical Design For Visual Systems” by Bruce H. Walker.

Users of OSLO Premium:

- Close the surface data spreadsheet.
- From the **File** menu, select **Lens database**,
- Select **Public**.

- In the window that opens, click on **LENS ID** and choose **Sort Up**.



- Using the scroll bar on the right find the lens with **LENS ID "Kellner Eyepiece"** As a check, the designer is shown as **bhw/WA**, the image surface number is **7.**

- Click on this line to call up the lens. The aberration curves are drawn automatically, and the listing is given in the text window when **Prescription** is selected.

- Open the surface data spreadsheet, and click on the gray **Wavelength** button.

- Right click to get the choice of pre-defined wavelengths, and select d, F and C respectively for the three wavelengths.

- In the text window click on **Wav**

```
*WAVELENGTHS
CURRENT    WV1/WW1      WV2/WW2      WV3/WW3
   1      0.587562     0.486133     0.656273
          1.000000     1.000000     1.000000
```

Users of OSLO EDU:

- From the menu header, choose **File > New lens.**

- Leave the file name as **untitled**, leave **Custom lens** as the option, and enter **6** as the number of surfaces.

Gen	Setup	Wavelength	Variables	Draw Off	Group	Notes
Lens: Kellner Eyepiece					Efl	28.010014
Ent beam radius	2.000000	Field angle	20.000000	Primary wavln		0.587562

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+20		3.6397e+19		AIR		
AST	0.000000		5.100000		2.000000	A	AIR		
2	153.000000		2.000000		8.000000		F4	C	
3	14.900000		8.000000		8.000000		BAK2	C	
4	-19.900000		22.300000		8.000000		AIR		
5	23.500000		6.000000		14.000000		BAK2	C	
6	0.000000		7.710000		14.000000		AIR		
IMS	0.000000		0.000000		9.800000				

- Fill in the surface data spreadsheet entries as shown. Check the Efl value to confirm that the data entries are correct.

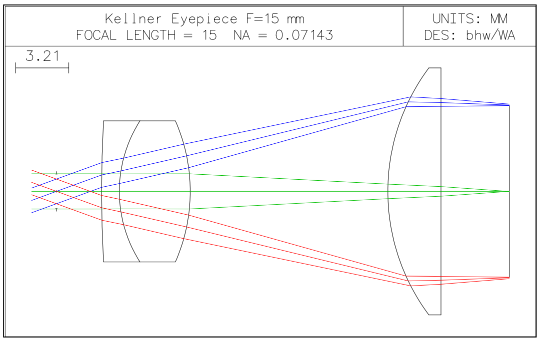
All users:

Note that the eyepiece has an object at infinity and an image at a finite distance. In other words, we are tracing the rays from the eye to the intermediate image, in the reverse direction of travel of the light. Surface 1 is defined as the aperture stop.

Scaling the eyepiece

The eyepiece must now be scaled to give the required focal length of 15 mm:

- In the surface data spreadsheet, click on **Draw Off** to open the Autodraw window (at which point **Draw Off** becomes **Draw On**).
- After **Lens:** assign a title: `Kellner Eyepiece F=15 mm`
- Right click on any of the surface buttons on the left, and choose **Scale Lens►Scale To New Focal Length ...**



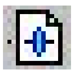
- Insert **15** (this lens is already specified in the default units of mm).
- Left click on the gray button to the right of the thickness column in the IMS row and select "Variable(V)".
- Click on **OK**.
- List the lens by clicking on **Len** in the text window.

```
*LENS DATA
Kellner Eyepiece F=15 mm
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ         --         5.3552e+19     1.9491e+19             AIR

 AST         --           2.731166       1.071046 A           AIR     Ent Pupil

   2      81.934981       1.071046       4.284182              F4 C
   3       7.979289       4.284182       4.284182            BAK2 C
   4     -10.656903      11.942157       4.284182             AIR

   5      12.584785       3.213137       7.497319            BAK2 C
   6         --           4.128880       7.497319             AIR

 IMS         --              --      V   5.221347                 *
```

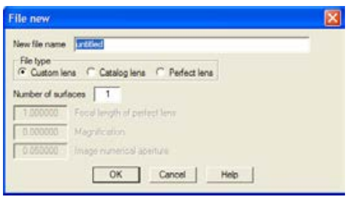
- Save the eyepiece in the **private/len/User_guide** directory with the name `bino_ep.len.`

Choosing a catalog objective

Rather than design an objective from scratch, the task will be to locate a suitable lens in the lens manufacturers' catalogs provided with the program. The focal length required is about 120 mm. While the entrance pupil diameter is 30 mm, allowance must be made for mounting, say 3 mm on the radius (larger than on an internal lens because of the need to provide a seal against moisture).

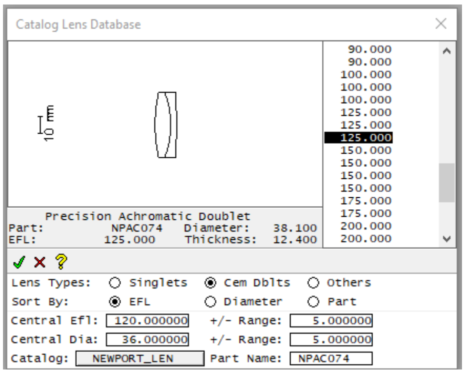


- Click on the third icon on the main window toolbar, which is the symbol for a new lens.
- In the dialog box which opens, click on **OK**.

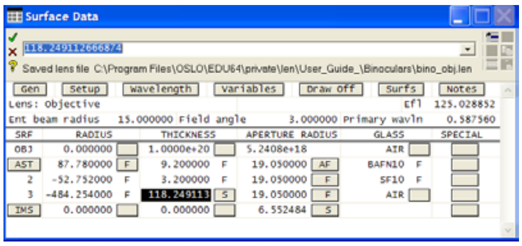


- In the surface data spreadsheet which opens, after **Lens**: assign a title (e.g. **Objective**)
- Change **Ent beam radius** to **15** mm.
- Change **Field angle** to **3** degrees.
- Left click on the gray surface button in the first column for surface 2 (**IMS**) to select the surface.
- Right click.
- From the drop-down menu, choose the option **Insert Catalog Lens...**

In the window which appears, make the following selections:



- First, at the bottom of the screen, for **Catalog:** select **NEWPORT-LEN**
- To find a cemented doublet, click on the button for **Lens types ⦿ Cem Dblts**
- Leave default **Sort By ⦿EFL.**
- Enter the **Central EFL** (focal length), **120 mm** and **+/- Range 5** mm
- Enter the **Central Dia**, **36** mm and **+/- Range 5** mm.
- Select the lens **NPACO74** with a focal length of **125** mm. The figure gives an idea of what you may see but catalog lenses can change over time due to supplier changing their inventory. You can select other doublets for this example with similar focal length.
- Click on the green tick, and the window will close.
- Click on the gray button **Group** at the top of the surface data spreadsheet to show the individual surfaces.
- Delete the non-functional first surface: Left click on the gray Srf button to select the line, right click on the gray button to create the pull-down menu, and select **Delete**. The aperture stop indicator (**AST**) on the surface number button will move to the first surface of the doublet.
- Set the image distance to the paraxial image distance by clicking on the gray button in the cell for the thickness of surface number 3 (the back focal distance). Select **Solve (S) > Axial ray height**, and after **Enter solve value** type **0**. The thickness value becomes 118.249113. An **S** will appear on the gray button next to this, indicating the presence of a paraxial "solve." What this means is that as long as the lens is rotationally symmetric and we are operating where paraxial optics is reasonable, then the distance to the next surface (in this case the image surface) will be adjusted so that the height of the paraxial marginal ray at the next surface is zero. In other words, the image will always be at the paraxial focus.
- If your text window does not have Slv available as an option, click on the left Setup Window/Toolbar button and select "Lens Data Tools". Then in the text window, click on Slv to confirm this definition.



```
*SOLVES
  3     PY        --
```

- Save the lens in the **private/len/User_guide** directory with the name `bino_obj.len`
- In the text window, click on **Len** to list the lens.

```
*LENS DATA
Objective
 SRF       RADIUS       THICKNESS   APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ        --        1.0000e+20    5.2408e+18              AIR

 AST     87.780000 F    9.200000 F    19.050000 AF       BAFN10 F *
  2     -52.752000 F    3.200000 F    19.050000 F          SF10 F
  3    -484.254000 F  118.249113 S    19.050000 F           AIR

 IMS        --             --           6.552484 S
```

- Check the lens prescription against the manufacturer's published catalog.

Combining the objective and the eyepiece

The first task is to combine objective and eyepiece without the prisms.

Users of OSLO EDU:

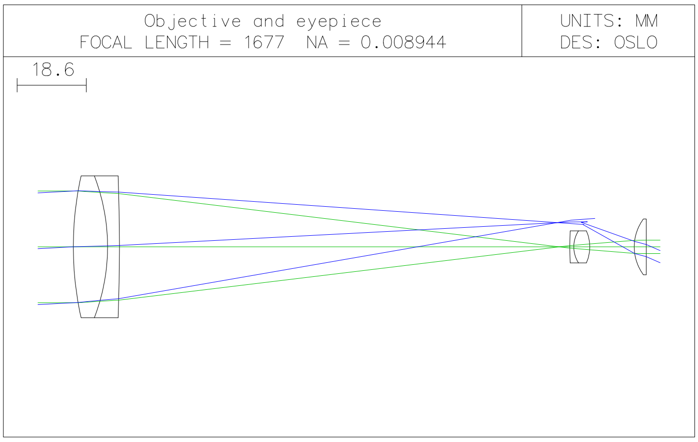
OSLO EDU can handle the number of surfaces after merging. However, the merging process OSLO uses with another lens file temporarily exceeds the ten-surface limit. So, a different way to combine must be used then the one seen next for OSLO Premium users. Note that inserting a lens file does work for OSLO EDU, these instructions are merely to overcome the surface limitation. OSLO Premium users can also use the method shown here for OSLO EDU users.

- Open the file with the eyepiece, **bino_ep**.
- Open the surface data spreadsheet.
- With the surface data spreadsheet open, select the data for surfaces 1 to 6 (1 is marked AST) by left clicking and dragging in the surface data spreadsheet.
- Click the button on the upper right corresponding to "Copy selected rows to the ss clipboard".
- Open the file with the objective, **bino_obj**.
- If necessary, open the surface data spreadsheet.
- If necessary, click on **Draw Off** to open the Autodraw window.
- Change the title to Objective and eyepiece.
- Left click on the IMS gray button in the surface data spreadsheet to select that row.
- In the upper right left click on the button corresponding to Paste ss clipboard above the first selected row.

Users of OSLO Premium:

- Ensure the file with the objective, **bino_obj** is open.
- Open the surface data spreadsheet.

- If necessary, click on **Draw Off** to open the Autodraw window.
- Change the title to **`Objective and eyepiece`**
- Left click on the surface button for the image surface (**IMS**). This will select surface 4, indicated by a bold surround.



- Right click on the gray button **IMS**, under **SRF**, to bring up the options menu.
- Choose **Insert Lens File ...**
- In the Merge lens file window, find the eyepiece file **bino_ep** and click on **Open**.

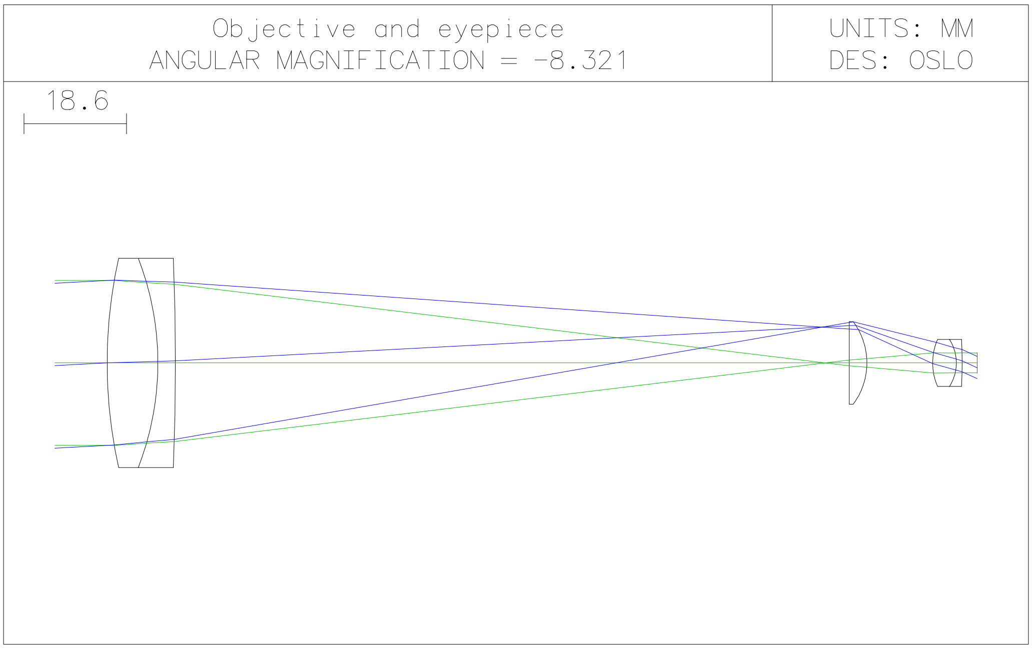
At this stage, of course, the eyepiece is now the wrong way round.

Lens: Objective and eyepiece				Efl	1.6772e+03
Ent beam radius	15.000000	Field angle	3.000000	Primary wavln	0.587560
SRF	**RADIUS**	**THICKNESS**	**APERTURE RADIUS**	**GLASS**	**SPECIAL**
OBJ	0.000000	1.0000e+20	5.2408e+18	AIR	
AST	87.780000 F	9.200000 F	19.050000 AF	BAFN10 F	
2	-52.752000 F	3.200000 F	19.050000 F	SF10 F	
3	-484.254000 F	118.249113 S	19.050000 F	AIR	
4	0.000000	2.734194	1.050164	AIR	N
5	82.025813	1.072233	4.288931	F4 C	
6	7.988135	4.288931	4.288931	BAK2 C	
7	-10.668717	11.955396	4.288931	AIR	
8	12.598736	3.216699	7.505630	BAK2 C	
9	0.000000	4.133458	7.505630	AIR	
IMS	0.000000	0.000000	2.616880 S		

- Select the seven surfaces of the eyepiece and the exit pupil (numbered 4 to **IMS**)
- Right click anywhere in this group.
- Select **Reverse**
- Click on **Gen** at the top of the surface data spreadsheet, and change **Evaluation mode** to **Afocal**. In afocal mode ray aberrations will be angular rather than transverse linear. Afocal mode does not consider the image surface thickness, which is disregarded. Change the exit pupil (surface 10) aperture radius to **`15/8`**
- Click on surface 10 **Special** gray button. Select **Surface Note (N)** and change the note to **`Exit pupil.`** Also under the surface 10 **Special** button, select **Surface control(F) > General** Change **Surface appearance in lens drawing:** to **Drawn**, and change the **Pen number** to **`4`** (i.e. red).
- Save the file with the name **bino_obj_ep.len**
- Click on **Len** in the text window header.

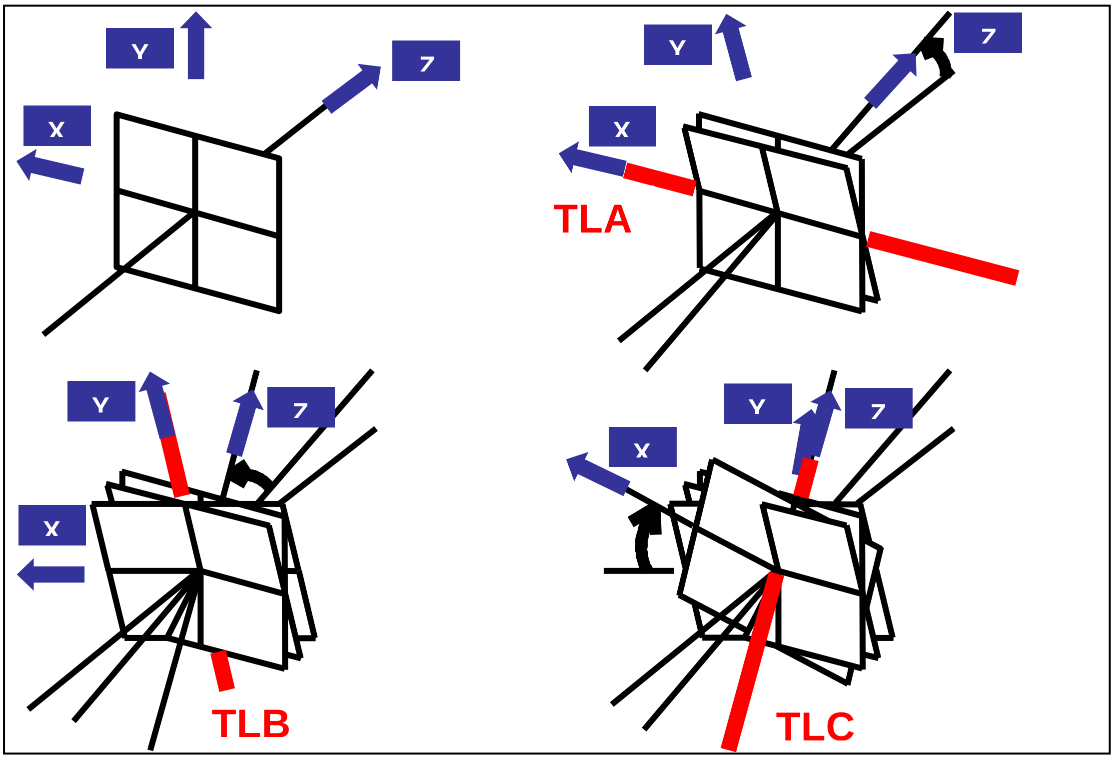
```
*LENS DATA
Objective and eyepiece
 SRF        RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ          --         1.0000e+20    5.2408e+18             AIR

 AST     87.780000 F     9.200000 F    19.050000 AF         BAFN10 F *
  2     -52.752000 F     3.200000 F    19.050000 F            SF10 F
  3   -484.254000 F  118.249113 S    19.050000 F             AIR

  4           --         4.133458       2.616880              AIR

  5           --         3.216699       7.505630             BAK2 C
  6     -12.598736      11.955396       7.505630              AIR

  7      10.668717       4.288931       4.288931             BAK2 C
  8      -7.988135       1.072233       4.288931               F4 C
  9     -82.025813       2.734194       4.288931              AIR

 IMS          --            --          1.875000                    * Exit Pupil
```

- Open the surface data spreadsheet and find the Autodraw window.



Surface decenters and tilts

Before modeling the prisms, we will look at how tilted and decentered surfaces are defined.



The gray button under **Special** in the surface data spreadsheet includes the option **Coordinates** where all this is found.

The default sequence is **Decenter, then tilt** in which case the sequence of displacements is:

1. Decenter by DCX along X axis, by DCY along Y axis, and by DCZ along Z axis, all in system units.
2. Tilt anticlockwise about the new X axis through an angle TLA (degrees)
3. Tilt anticlockwise about the new Y axis through an angle TLB (degrees)
4. Tilt clockwise about the new Z axis through an angle TLC (degrees).

The tilts are shown in the diagram above. If the **Tilt, then decenter** option is chosen, the order is reversed.

The effect of decentering or tilting a surface is also to decenter or tilt not only the surface and its local coordinate axes, but also all the subsequent surfaces in the system.

To tilt only a component or group of surfaces, on the first surface apply the tilt and select the option **Use base coordinate system for coordinate returns to this surface: YES.** On the last surface, select **Coordinate return: YES** and **Return to surface:** [first surface number].

To tilt a single surface, apply the tilt, then select **Coordinate return: YES, Return to surface:** [default value, the same surface number] and **Use base coordinate system for coordinate returns to this surface: YES.**

Adding a right angle prism

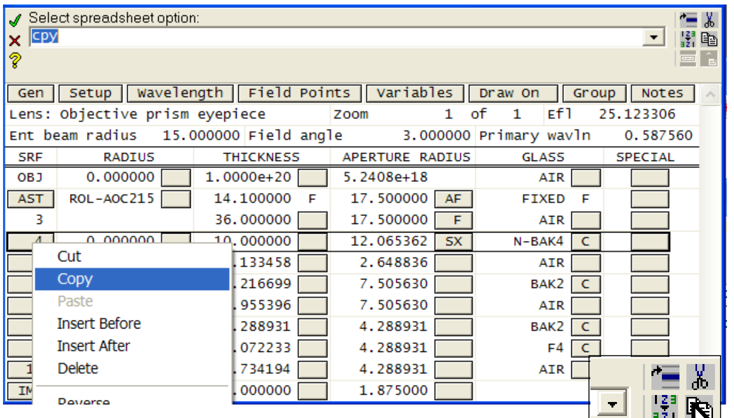
The task is to model a simple 90° prism. The measurement of the external dimensions of the binoculars, allowing 3 mm for the case, suggests that the apex of the first prism (20 mm deep) will be 70 mm behind the front surface of the objective (thickness 12.4 mm), leaving an air space of 70 - 12.4 - 20 = 37.6 mm between the rear of the objective and the prism.

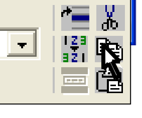
- Open the surface data spreadsheet.
- Change the lens title to **`Objective prism eyepiece`**
- Change the thickness for surface 3 to **`37.6`**. The solve flag (S) disappears.
- Now add an extra surface before surface 4: Left click on the gray surface button for surface 4, and then either right click on the same button and select **Insert before**, or use the shortcut **Shift-space**.

Users of OSLO EDU will not be able to add the extra surface to the straight-through binocular, since it will cause the surface count limit (10) to be exceeded. However, starting with the file consisting of the objective alone (**bino_obj*****) the exercise of adding the first prism can proceed as described here.***

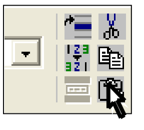
- Change the thickness for the new surface 4 to **`10`** mm.
- Under the gray button in the column labeled **Aperture Radius** for this surface (surface 4), select **Special Aperture Data (X).** Leave the **Ap Id**: as **`0`**. Change the shape to **Rectangle**, keep the Action as **Transmit**, leave the **Group:** as **`0`**, and set the semi-aperture dimensions to:

Xmin = **`-10`** **Xmax** = **`10`** **Ymin** = **`-10`** **Ymax** = **`10`** **Angle** = **`0.0`**





- Change the medium for surface 4 from air to glass: Click on the gray **GLASS** button, select **Catalog > Schott > N-BAK4**. ***(For some versions of OSLO the current Schott catalog will be in the directory be Schott 2004 rather than Schott).***
- Select the entire row of surface 4. Then right click, selecting **Copy**. Otherwise right click on the copy icon on the right of the spreadsheet, shown in the diagram.



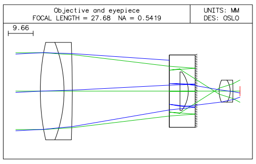
- Click on the gray surface button for surface 5. Right click and select **Paste.** Otherwise right click the paste icon. The new surface is added before the one highlighted.
- Once more, click on the gray surface button for surface 5, right click and select **Paste.**
- Change the **Thickness** for surface 5 to **`-10`**.

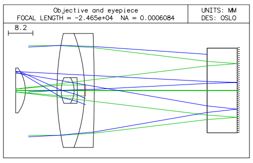
- Under the **Aperture Radius** gray button for surface 5, select **Special Aperture Data** and set:

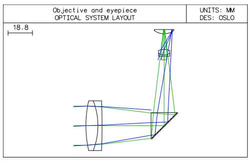
  Ymin = **-14.14** **Ymax** = **14.14**

leaving everything else in this dialog box unchanged.

- From the gray button under **Glass** for surface 5, select **Reflect (hatch).**







- Under **Glass** for surface 6, type **AIR**

- To change the thickness for surface 6 to an axial ray height solve, click on the gray button next to thickness for surface 6, and select **Solve (S) > Axial ray height**, and after **Enter solve value** type **0**.

  - Under **Special** for surface 5, select **Coordinates (C)**. Set **TLA** = **-45**, and **Tilt and Bend: Yes.** Leave everything else as default.

In most cases, tilting a surface rotates the coordinate system of the airspace after that surface, and all subsequent surfaces, through the same angle. However if **Tilt and Bend** is specified, the rotation is through twice this angle, corresponding to the law of reflection.

  - In the text window, click on **Ape** to list the special aperture data for the three surfaces of the prism.

```
*APERTURES
 SRF   TYPE APERTURE RADIUS
...
  4      CMP    12.022663

     Special Aperture Group 0:
     0  ATP     Rectangle  AAC     Transmit  AAN        --
        AX1    -10.000000  AX2    10.000000  AY1    -10.000000   AY2     10.000000

  5      CMP    11.590322

     Special Aperture Group 0:
     0  ATP     Rectangle  AAC     Transmit  AAN        --
        AX1    -10.000000  AX2    10.000000  AY1    -14.140000   AY2     14.140000

  6      CMP    11.157981

     Special Aperture Group 0:
     0  ATP     Rectangle  AAC     Transmit  AAN        --
        AX1    -10.000000  AX2    10.000000  AY1    -10.000000   AY2     10.000000
```

- Click on **Len** to list the lens data. Note that the three solved aperture radius values seen on the top-level spreadsheet for surfaces 4, 5 and 6 remain unchanged by the definition of special apertures (X); these values are ignored.

```
*LENS DATA
Objective prism eyepiece
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ        --          1.0000e+20    5.2408e+18              AIR

 AST     87.780000 F     9.200000 F    19.050000 AF        BAFN10 F *
  2     -52.752000 F     3.200000 F    19.050000 F           SF10 F
  3    -484.254000 F    37.600000      19.050000 F            AIR

  4         --          10.000000      12.022663 SX        N-BAK4 C
  5         --         -10.000000      11.590322 SX    REFL_HATCH    *
  6         --         -67.900739 S    11.157981 SX           AIR

  7         --           4.133458       2.616880              AIR

  8         --           3.216699       7.505630             BAK2 C
  9     -12.598736      11.955396       7.505630              AIR

 10      10.668717       4.288931       4.288931             BAK2 C
 11      -7.988135       1.072233       4.288931               F4 C
 12     -82.025813       2.734194       4.288931              AIR

 IMS        --             --           1.875000                  * Exit Pupil
```

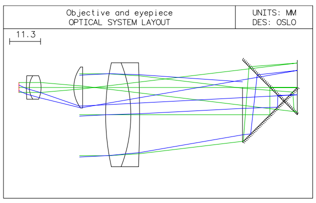
- Click on **Spe** to list the surface notes, the coordinate (tilt) data and the surface tag (pen color etc.) data:

```
*SURFACE NOTES
 13    Exit pupil

*TILT/DECENTER DATA
  5      DT    1          DCX       --       DCY       --       DCZ       --
         BEN              TLA   -45.000000   TLB       --       TLC       --

*SURFACE TAG DATA
  1      LMO ELE  (3 surfaces)
 13      DRW ON
         LDP    4
```

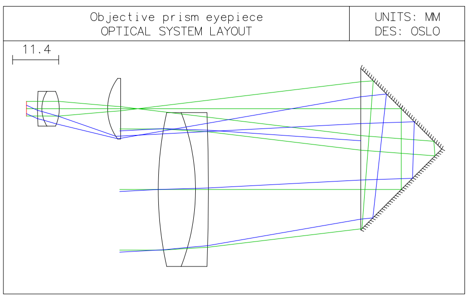
The eyepiece is incorrectly modeled since the signs of all curvatures and thicknesses should be inverted. For the time being, however, we will ignore this and proceed to the next stage.

Converting the prism to a Porro prism

The Porro prism has two reflecting surfaces at right angles to each other.



- Select the entire row of surface 5. Then right click, selecting **Copy**.
- Click on the gray surface button for surface 5. Right click and select **Paste.**
- Using the surface data spreadsheet, change the thickness for surface 5 to **-20** mm, and the thickness for surface 6 to **10** mm.
- Save with the name **bino_porro.len.**
- In the text window click on **Len** and **Spe.**

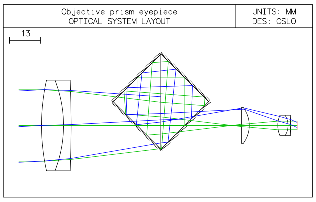


```
*LENS DATA
Objective prism eyepiece
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS   SPE  NOTE
 OBJ         --         1.0000e+20     5.2408e+18             AIR

 AST     87.780000 F     9.200000 F    19.050000 AF        BAFN10 F *
  2     -52.752000 F     3.200000 F    19.050000 F           SF10 F
  3   -484.254000 F    37.600000      19.050000 F            AIR

  4          --         10.000000      12.022663 SX        N-BAK4 C
  5          --        -20.000000      11.590322 SX    REFL_HATCH   *
  6          --         10.000000      10.725639 SX    REFL_HATCH   *
  7          --         55.152366 S    10.293298 SX           AIR

  8          --          4.133458       2.616880              AIR

  9          --          3.216699       7.505630             BAK2 C
 10    -12.598736       11.955396       7.505630              AIR

 11     10.668717        4.288931       4.288931             BAK2 C
 12     -7.988135        1.072233       4.288931               F4 C
 13    -82.025813        2.734194       4.288931              AIR

 IMS         --            --           1.875000                    * Exit Pupil

*SURFACE NOTES
 14    Exit Pupil

*TILT/DECENTER DATA
  5      DT     1         DCX       --        DCY       --       DCZ       --
         BEN              TLA    -45.000000   TLB       --       TLC       --
  6      DT     1         DCX       --        DCY       --       DCZ       --
         BEN              TLA    -45.000000   TLB       --       TLC       --

*SURFACE TAG DATA
  1      LMO ELE  (3 surfaces)
 14      DRW ON
         LDP    4
```

Adding a second Porro prism

We will now add the second Porro prism. ***Note that users of OSLO EDU will have reached the 10-surface limit even without the eyepiece, and will have to delete the objective (surfaces 1 to 3) to complete this section, modifying the surface numbering accordingly.***

- In the surface data spreadsheet, select surfaces 4-7.
- Right click, selecting **Copy**.
- Click on surface 8 to highlight the whole surface, right-click, and select **Paste.**

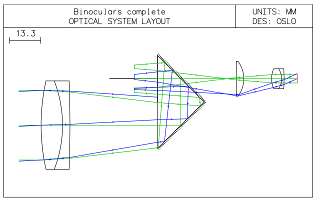


- Under **Thickness** for surface 7, enter **0**. This automatically deletes the thickness solve on that surface.
- The aperture of surface 12 is not sufficiently large. Convert it to a solved aperture by just setting the **Aperture Radius** for surface 8 to **0**. The solved value (6.552484) replaces it immediately.
- Surface 18 is not at the true exit pupil. Click on the gray button under **Thickness** for surface 17, and select **Solves (S) > Chief ray height...** and enter **0.**

Completing the design

The model does not include the 90º rotation about the optical axis of the second prism relative to the first.

- To rotate the second prism Z axis through an angle of 90°, under **Special** for surface 8, select **Coordinates (C),** and set the tilt angle about the z-axis, **TLC** = `90` (degrees).
- Change the lens title to: `Binoculars complete`.
- Save with the file name **bino_complete.len**
- Enter the commands: `drl;drr 0;drr 1` to draw in 2 dimensions.



The full prescription is obtained by clicking on **Len Spe** and **Ape** in the text window.

```
*LENS DATA
Binoculars complete
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ         --         1.0000e+20    5.2408e+18              AIR

 AST     87.780000 F     9.200000 F    19.050000 AF        BAFN10 F *
  2     -52.752000 F     3.200000 F    19.050000 F           SF10 F
  3    -484.254000 F    37.600000      19.050000 F            AIR

  4          --         10.000000      12.022663 SX         N-BAK4 C
  5          --        -20.000000      11.590322 SX     REFL_HATCH   *
  6          --         10.000000      10.725639 SX     REFL_HATCH   *
  7          --             --         10.293298 SX           AIR

  8          --         10.000000      10.293298 SX         N-BAK4 C
  9          --        -20.000000       9.860957 SX     REFL_HATCH   *
 10          --         10.000000       8.996274 SX     REFL_HATCH   *
 11          --         29.655619 S     8.563933 SX           AIR

 12          --          4.133458       6.552484 S            AIR

 13          --          3.216699       7.505630             BAK2 C
 14     -12.598736      11.955396       7.505630              AIR

 15      10.668717       4.288931       4.288931             BAK2 C
 16      -7.988135       1.072233       4.288931               F4 C
 17     -82.025813       5.649290 S     4.288931              AIR

 IMS         --             --          1.875000                     * Exit Pupil

*SURFACE NOTES
 18     Exit Pupil

*TILT/DECENTER DATA
  5      DT     1        DCX        --        DCY        --       DCZ        --
         BEN             TLA   -45.000000     TLB        --       TLC        --
  6      DT     1        DCX        --        DCY        --       DCZ        --
         BEN             TLA   -45.000000     TLB        --       TLC        --
  8      DT     1        DCX        --        DCY        --       DCZ        --
                         TLA        --        TLB        --       TLC    90.000000
  9      DT     1        DCX        --        DCY        --       DCZ        --
         BEN             TLA   -45.000000     TLB        --       TLC        --
 10      DT     1        DCX        --        DCY        --       DCZ        --
         BEN             TLA   -45.000000     TLB        --       TLC        --
```

```
*SURFACE TAG DATA
  1     LMO ELE  (3 surfaces)
 18     DRW ON
        LDP    4

*APERTURES
 SRF   TYPE APERTURE RADIUS
  0     SPC   5.2408e+18
  1     FIX    19.050000
  2     FIX    19.050000
  3     FIX    19.050000
  4     CMP    12.022663

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -10.000000  AY2    10.000000

  5     CMP    11.590322

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -14.142136  AY2    14.142136

  6     CMP    10.725639

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -14.142136  AY2    14.142136

  7     CMP    10.293298

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -10.000000  AY2    10.000000

  8     CMP    10.293298

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -10.000000  AY2    10.000000

  9     CMP     9.860957

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -14.142136  AY2    14.142136

 10     CMP     8.996274

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -14.142136  AY2    14.142136

 11     CMP     8.563933

     Special Aperture Group 0:
     0  ATP    Rectangle  AAC     Transmit  AAN       --
        AX1   -10.000000  AX2    10.000000  AY1   -10.000000  AY2    10.000000

 12     CMP     6.552484
 13     SPC     7.505630
 14     SPC     7.505630
 15     SPC     4.288931
 16     SPC     4.288931
 17     SPC     4.288931
 18     SPC     1.875000
```

Chapter 5 - Graphical analysis

Introduction

In general, the graphics facilities in OSLO are of the most frequently generated using the icons in the toolbars of the individual graphic windows. Some facilities, however, can only be accessed from the menu headers, and some only by calling up CCL commands from the command line.

A comprehensive catalog of the graphics facilities will be found in the Graphics Reference in the appendix at the end, together with instructions as to how each may be accessed. In this chapter only lens drawing and ray intercept coordinate reports will be discussed in detail.

Opening a new graphics window

This exercise shows how a new graphics window can be opened in the top left corner of the main window, just under the command window.

- From the main window select the **Window** menu header.
- Choose **Graphics > Open** and type the following responses into the command window:

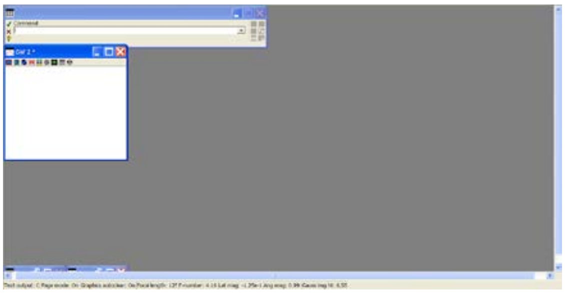
  Enter graphics window number: `0`

  Enter window width: `320`

  End to window height: `300`

  Enter window x: `0`

  Enter window y: `120`



Note that the new window has a dark blue title bar, containing the letters GW 2 *. GW means that it is a graphics window with no updateable content. The * symbol means that it is the current window for graphical output. The coordinate system defines x =0, y = 0 as the top left corner, and the command window covers the area x = 0 to 600, y = 0 to 100. The point x = 960 (1420 for wide screens), y = 710 is the bottom right position which can be seen without scrolling.

Labeling a graphics window

- From the main window select the **Window** menu header.
- Choose **Graphics > Title...** and type the following response into the command window:
- **Enter window title:** `Colors.`

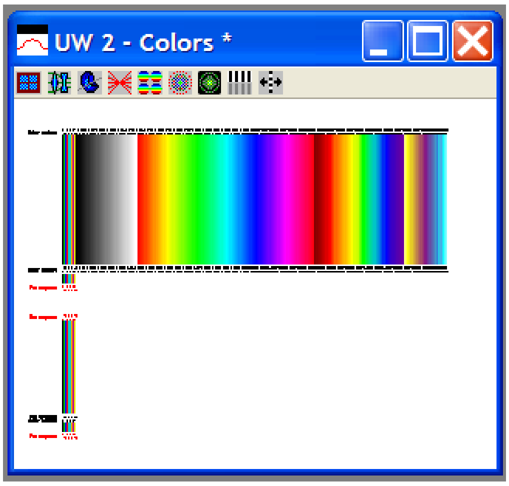
The title appears in the blue bar at the top of the window. In practice graphics windows are titled automatically by the graphics command associated with the relevant icon in the graphics window.

Generating a plot

- Select the **Tools** menu header.
- Choose **Plotting toolkit > Colors and Pens**.

  This executes the CCL command **colors**, which is stored in the file **graph_tools.ccl** in the **public/ccl** directory. It shows the pen numbering used in graphics plots.

  Notice that the letters in the title bar have now changed to **UW**, meaning that the graphics window is updateable.

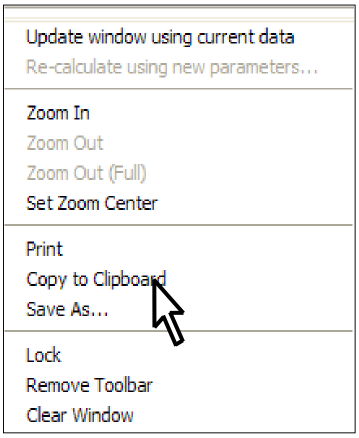


Saving a plot

- Right click on the window and choose **Save As ...**
- Save the file in any format. The size of the file stored will differ according to the format chosen. For comparison, the file sizes for the Colors and Pens graphic are shown:

Windows bitmap	BMP	164 kB
Compressed bitmap	RLE	29 kB
HP-GL format	HGL	29 kB
Windows metafile	WMF	118 kB
Placeable Windows metafile	WMF	118 kB
Enhanced Windows metafile	EMF	182 kB

Cutting and pasting a plot



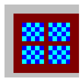
- Right click on the window and choose **Copy to Clipboard.**
- Open a Word document or PowerPoint presentation, right click, and choose **Paste.**
- If there are problems with the size of the image pasted into the new application, look again at the Graphics Preferences in Chapter 2.

Lens drawing

Drawing a lens in 2D

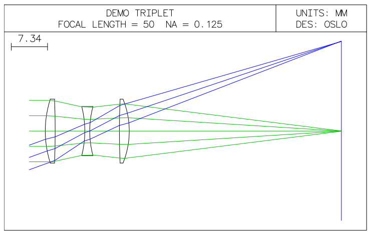
This exercise will demonstrate some of the 2D drawing options, using the standard triplet lens as an example.

- Click on the Open Lens icon in the main window toolbar.
- Open the file in the **Private** directory, **trip.len**



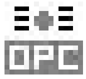
- In the graphics window, click on the **Setup Window/Toolbar** icon.
- Select the **Lens Drawing** toolbar.

- Click on the **Draw system (2D)** icon.



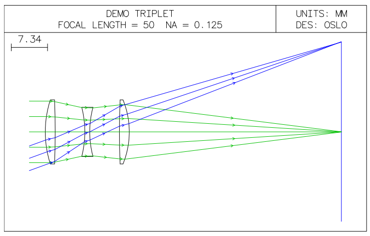
This gives a lens drawing including rays as the default. The corresponding icon in the Standard Tools toolbar gives the option of a 2D (plan) drawing without rays.

Various options to enhance this drawing will now be shown.



- Click, in the main window toolbar on the icon shown here for **Edit Lens Drawing Conditions.**
- On the fifth line, against **Image space rays:** select **Draw rays to image surface.** The button then reads **Image srf**
- From the menu header **Select File > Preferences > Preference groups > Graphics...** and choose from the menu **Use labels on graphics.** Select **Off.**

- Open the surface data spreadsheet.
- Click on the gray button under **Special** for surface **7 (IMS).**
- Select **Surface Control (F) > General**
- On the second line, against **Surface appearance in lens drawings:** select **Drawn.** Set the **Pen number for surface in lens drawings** as **3** (blue).



- Close both spreadsheets.

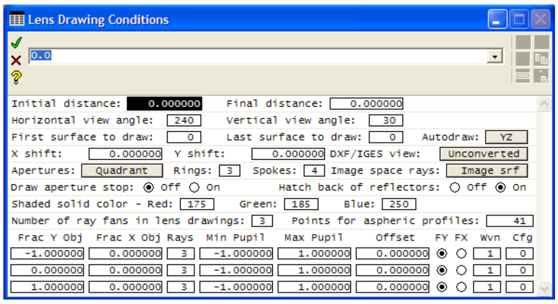
- Once again click on the **Draw system (2D)** icon to draw the lens.

- Click again on the icon in the main window toolbar for **Edit Lens Drawing Conditions.**

In the ray drawing table at the foot of the spreadsheet, change the three values of the **Frac. Y Obj** (FBY) to `0.0, -1.0, +1.0` respectively. Also change the number of rays in the second fan (**Rays**) from **0** to **3**, **Min pupil** to **-0.4**, and **Max pupil** to **0.4**.

In this spreadsheet, for each successive ray fan (where the number of rays plotted is non-zero) the pen colors cycle through the sequence:

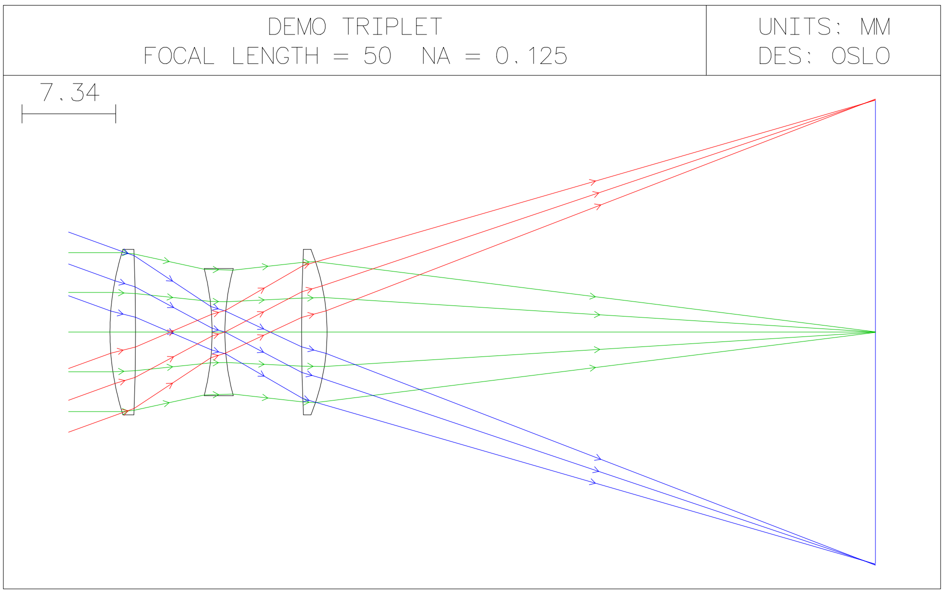
1. **Green**
2. **Blue**
3. **Red**
4. **Light-Blue**
5. **Orange**
6. **Violet**
7. **Yellow**
8. **Black**



- Close the **Edit Lens Drawing Conditions** spreadsheet.
- From the **Lens** menu header, select **Show Operating Conditions .. > Lens Drawing**

```
*CONDITIONS: LENS DRAWING
   Initial distance:              --       Final distance:               --
   Horizontal view angle:        240       Vertical view angle:           30
   First surface to draw:          0       Last surface to draw:           0
   X shift of drawing:            --       Y shift of drawing:            --
   Drawn apertures (solid):  Quadrant      Image space rays:       Image srf
   Rings in aperture (solid):      3       Spokes in aperture (solid):     4
   Number of field points (rays):  3       DXF/IGES file view:   Unconverted
   Draw aperture stop location:  Off       Hatch back side of reflectors: On
   Red value for shaded solid:   175       Green value for shaded solid: 185
   Blue value for shaded solid:  250       Points for aspheric profile:   41
   Autodraw Options:          YZ Profile
   Fpt Frac Y Obj Frac X Obj Rays Min Pupil  Max Pupil    Offset   Fan Wvn Cfg
    1      --         --       5   -1.00000   1.00000       --      Y   1   0
    2   -1.00000      --       3   -0.40000   0.40000       --      Y   1   0
    3    1.00000      --       3   -0.40000   0.40000       --      Y   1   0
```

- Draw the lens in two dimensions by clicking on the icon for **Draw system (2D)**.

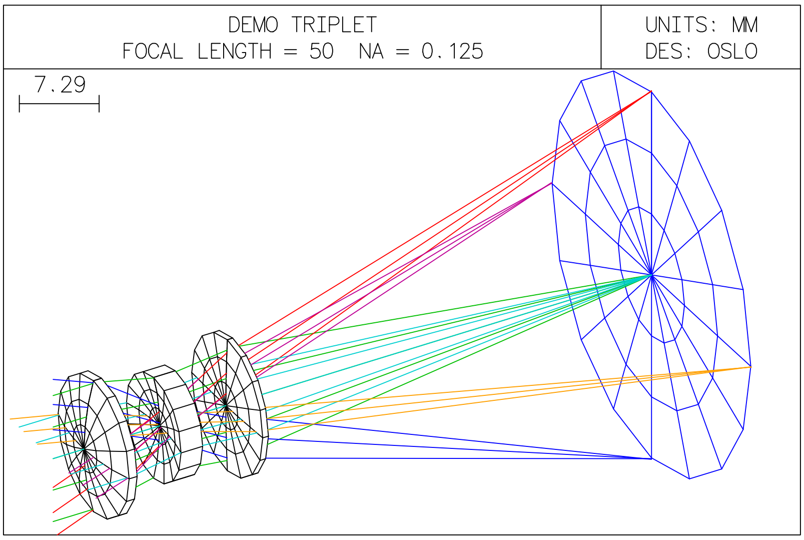


Drawing a lens in 3D

- Open the **Edit Lens Drawing Conditions** spreadsheet again.
- On the fifth line, for **Apertures:** change **Quadrant** to **Full apertures**. For **Number of ray fans in lens drawings** enter **6**, then scroll down to enter the three new fans with **Frac X Obj** = **0.0, -1.0, 1.0** respectively. For the three fans, specify **5, 3 and 3** rays and for the last two fans, change **Min pupil** to **-0.4,** and **Max pupil** to **0.4**.
- Select the radio button for **FX** for the last three fans.
- Close the **Edit Lens Drawing Conditions** spreadsheet.
- To list these values, from the **Lens** menu header, select **Show Operating Conditions > Lens Drawing.**

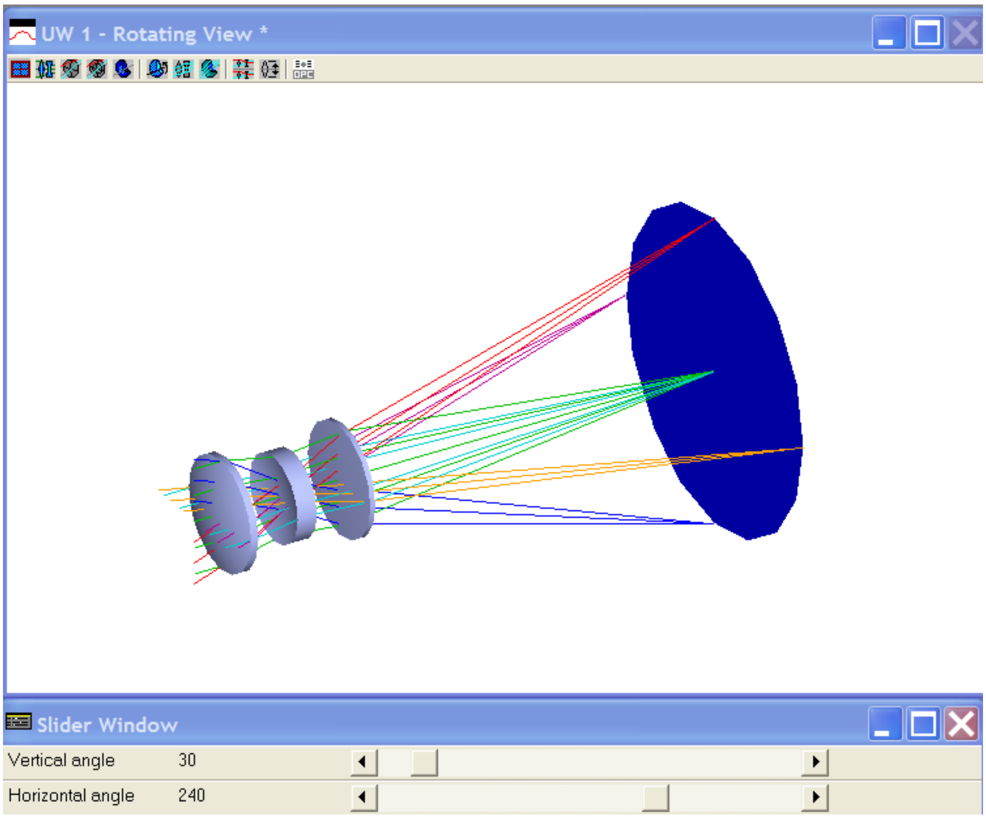
```
*CONDITIONS: LENS DRAWING
   Initial distance:             --        Final distance:               --
   Horizontal view angle:          240     Vertical view angle:            30
   First surface to draw:            0     Last surface to draw:            0
   X shift of drawing:           --        Y shift of drawing:           --
   Drawn apertures (solid):       Full     Image space rays:        Image srf
   Rings in aperture (solid):        3     Spokes in aperture (solid):      4
   Number of field points (rays):    6     DXF/IGES file view:     Unconverted
   Draw aperture stop location:    Off     Hatch back side of reflectors:  On
   Red value for shaded solid:     175     Green value for shaded solid:  185
   Blue value for shaded solid:    250     Points for aspheric profile:    41
   Autodraw Options:           YZ Profile
   Fpt Frac Y Obj Frac X Obj Rays Min Pupil  Max Pupil   Offset  Fan Wvn Cfg
    1       --         --      5   -1.00000   1.00000     --      Y   1   0
    2    -1.00000      --      3   -0.40000   0.40000     --      Y   1   0
    3     1.00000      --      3   -0.40000   0.40000     --      Y   1   0
    4       --         --      5   -1.00000   1.00000     --      X   1   0
    5       --      -1.00000   3   -0.40000   0.40000     --      X   1   0
    6       --       1.00000   3   -0.40000   0.40000     --      X   1   0
```

- Click on the icon for **Draw system (3D solid model).**

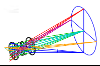
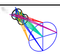
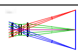
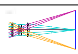
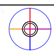


Drawing a lens in 3D with sliders

- Click on the icon for **Draw system (3D w/slider)**
- Select **Shaded solid.**



- It may be necessary to extend the slider bars to make the slider tracks visible.
- Adjust the sliders according to the following table:

Vertical view angle	Horizontal view angle	Description	Example
30º	**240º**	**Default**	
30º	**330º**	**Isometric**	
0º	**270º**	**Y - Z (2D plan view)**	
90º	**270º**	**X - Z**	
0º	**360º**	**X - Y view from image**	

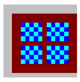
If the lens is saved with a particular 3D view in force, the values of the view angles will be stored with the lens and used in subsequent 3D drawings. The horizontal and vertical view angles may also be set in the **Edit Lens Drawing Conditions** spreadsheet.

Ray intercept curves analysis

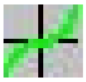
The importance of these curves for diagnosis of aberration problems cannot be overstated, so a detailed description will be given here of this analysis. The lens used for the graphs in this section is the objective of the binoculars modeled in chapter 3.

Ray analysis (RIC)

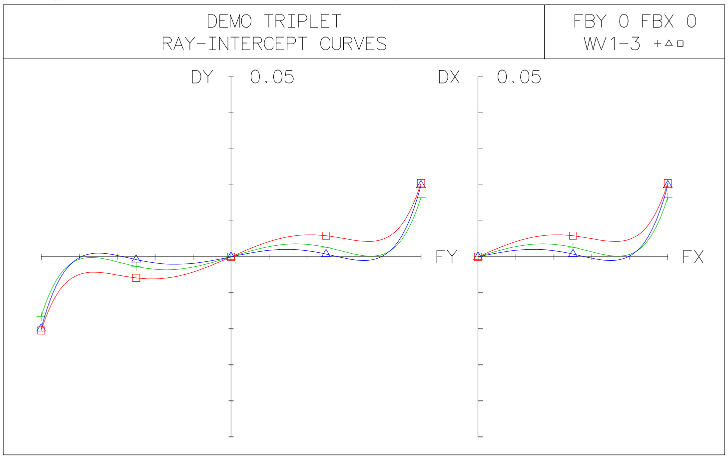
- In the graphics window, click on the **Setup Window/Toolbar** icon.



- Select the **Ray Analysis** toolbar.



- Click on the icon for **RIC Plot.** This gives a set of curves representing the transverse ray aberrations for the default field point, which is on axis (FBY = 0.0). The left hand graph gives the plot of transverse ray aberrations (DY) in the meridional section (the Y - Z section) at different heights (FY) in the pupil. The right hand graph gives the same information in the orthogonal plane - that is, DX as a function of FX. The three curves are colored according to the wavelengths, which, in the visible at least, are representative provided the order in which the wavelengths are defined is middle-short-long corresponding to green-blue-red.



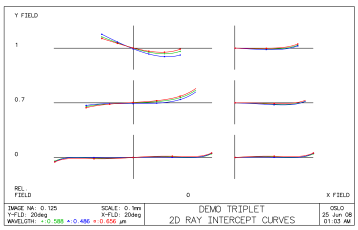
If the system is defined as afocal (see under the **Gen** button in the surface data spreadsheet) the aberrations are angular values DYA and DXA, expressed as direction tangents.

Ray intercept curves for 2D field points

Users of OSLO EDU and OSLO Light should skip this section

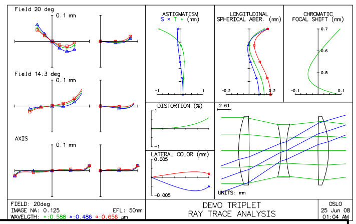
- Click on the icon for **RIC vs Field Points.**

This gives the graphs laid out in two dimensions according to the relative field coordinates FBX, FBY. In this case, three graphs are given for the three field points defined for this lens, which are (reading from the bottom) FBY = 0.0 (on axis), FBY = 0.7 and FBY = 1.0 (edge of field). The left-hand column gives DY as a function of FY, the right-hand column plots DX against FX.



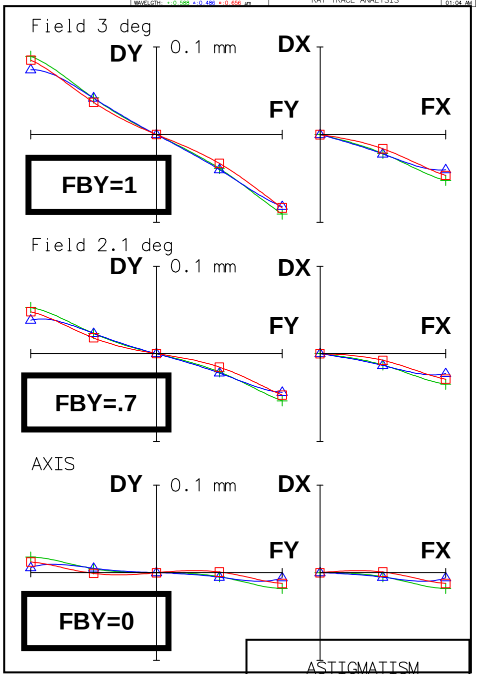
Ray intercept curves report graphic

- Click on the icon for **RIC Report Graphic.** This icon also appears on the **Standard Tools** toolbar. The analysis results are shown as 6 graphs within the same window, plus a 2D lens drawing.

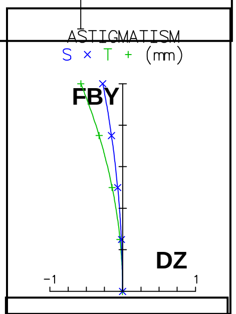


1. The left-hand group (unlabeled) gives the same ray intercept curves for three field points as the ray intercept curves for 2D field points.

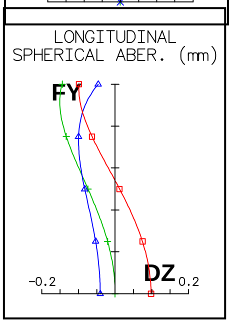
   This set of curves gives the relationship between the ray aberrations and their radial position in the pupil. If more than three wavelengths are specified, up to 12 sets of curves will be drawn, with different symbols as well as different colors to distinguish them.
   Most of the other information in the report (apart from distortion) can be deduced from these curves.
   A designer can use these curves as a diagnostic tool to analyze the different types of aberration. This analysis is important, since different aberrations require different measures for their correction. However these graphs do have limitations. For example, they do not indicate the aberrations of rays in the four quadrants between the two orthogonal planes.



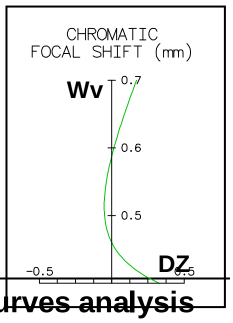
2. The astigmatism curves give the variation of paraxial focus across the field for the meridional section (the Y-Z section, labeled T) and the sagittal section (the X-Z section, labeled S). Results are only shown for the mean wavelength. This curve can be plotted as a stand-alone, either monochromatically or in 3 colors, using the menu header:
   - **Evaluate > Ray fans > Single field point ...**
   - At the top, select **Field sags**.
   - Choose either **Monochromatic** or **Polychromatic.**
   - Click on **OK.**



3. The three curves for longitudinal spherical aberration give the movement of the focal point along the axis for different radii in the pupil, for the axial image point only, corresponding to the three wavelengths.

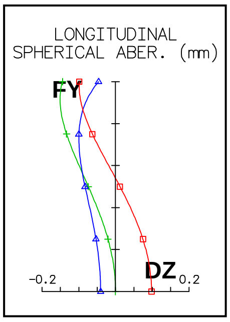


   The curves for chromatic focal shift represent the axial beam paraxial longitudinal focal variation with wavelength over the range 0.4 to 0.7 µm - or over a different range if other

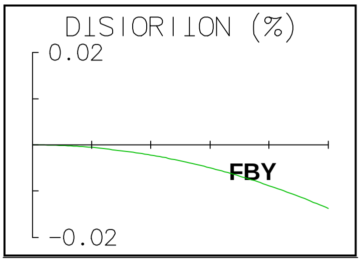


wavelengths are specified. Alternatively, for OSLO Standard and OSLO Premium users, this curve can be plotted as a stand-alone, in slightly different format, using the menu header:

- **Evaluate > Ray fans > Other ray analysis ...**
- From the menu select **Chromatic focal shift...**
- Enter a wavelength range (or zeros for default)**.**
- Click on **OK.**

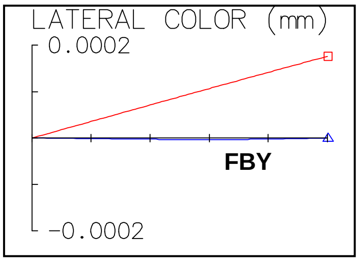


4. Longitudinal spherical aberration curves indicate the errors in focus DZ of the axial beam as a function of the pupil height DY. Curves are given for the three specified wavelengths. The graph is plotted on its own via the menu header:
   - **Evaluate > Ray fans > Single field point ...**
   - At the top, choose **Longitudinal spherical...**
   - Click on **OK.**



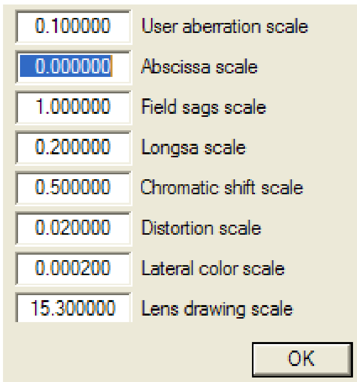
5. The curve for distortion shows the departure from the paraxial magnification as a function of field height. The distortion graph can be plotted alone in a different format using the menu header:
   - **Evaluate > Ray fans > Single field point ...**
   - At the top, choose **Distortion**
   - Choose either **Monochromatic** or **Polychromatic.**
   - Insert a value for the aberration scale (in %).
   - Click on **OK.**

The plots obtained from OSLO EDU and OSLO Light are different from the one shown here.



6. The curve for lateral color shows the difference between the heights of the red and green rays, and between the blue and green rays, as a function of field height. The graph is not available as a stand-alone.

To control all the aberration scales, the RIC report graphic command may be called from the main menu header.



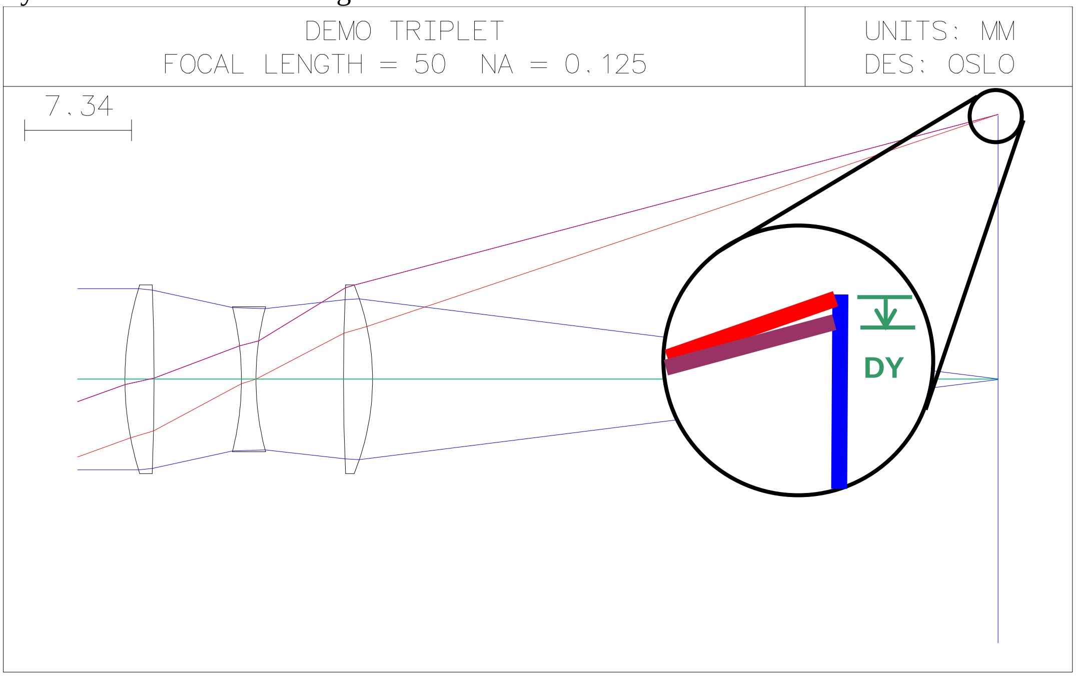
- From the **Evaluate** menu header select **Other ray analysis>Report Graphic..:**
- Fill in the spreadsheet with the required values. The value of the abscissa scale is omitted as it only applies to graphs where curves are plotted against h-tan U rather than DY.
- Click on **OK.**

Chapter 6 - Numerical analysis

Introduction

This chapter deals with the text window and the spreadsheet buffer which lies under it. In order to illustrate the methods of numerical analysis, a simple task concerning the demonstration triplet lens supplied with the program will be carried out:

For the triplet lens supplied with the program, calculate the transverse ray aberration of the outermost ray transmitted at the edge of the third component at the edge of the field, at the central (green) wavelength.
Also estimate the transmittance at the extreme field, as a percentage of the axial transmittance.
The transverse ray aberration of an off-axis ray in the meridional section is the distance from the point where this ray intersects the image plane, to the intersection point of the pupil ray. This is shown in the diagram.



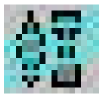
Before we can begin the task we need to locate the edge ray concerned in terms of its relative pupil height coordinate FY.

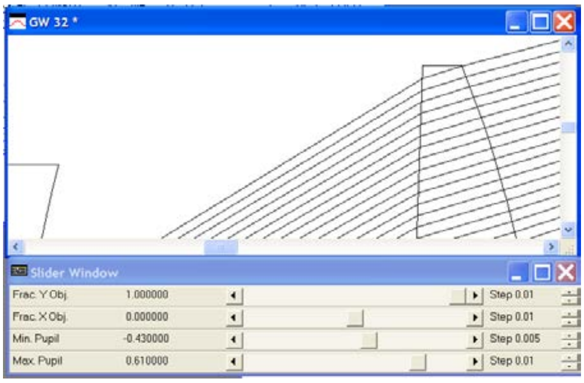
Finding the edge rays

- Open the lens in the private directory `trip.len`. Alternatively it will be found in the public directory as **/public/demo/LT/demotrip.len.**
- In the text window, click on **Ape** to list the apertures. The indication **CHK** for surfaces 1 and 6 means that in the ray analysis which follows the rays which lie outside these checked apertures will be obstructed. (Checked clear apertures are indicated by a **K** in the **Clear Aperture Radii** column of the surface data spreadsheet).

*APERTURES

SRF	TYPE	APERTURE RADIUS	
0	SPC	3.6397e+19	
1	SPC	6.500000	CHK
2	PKP	6.500000	
3	SPC	5.000000	
4	SPC	5.000000	
5	SPC	6.500000	
6	SPC	6.500000	CHK
7	CMP	18.170326	





- In the graphics window, click on the **Setup Window/Toolbar** icon, and select the **Lens Drawing** menu.
- Click on the icon for **View Ray Fans (2D) - Interactive**.
- To define the point in the field as the edge of the field, set the slider-wheel for **Frac Y Obj** to **1.0,** and leave the slider-wheel for **Frac X Obj** at **0.0.**
- Adjust the slider-wheels for **Min pupil** and **Max pupil** until the extreme rays of the bundle just pass through the first and last surfaces respectively.
- Note the values of the fractional pupil height for these edge rays: -0.43 and+0.61. The latter is the value of FY needed for this problem.

Instead of this procedure, users of OSLO Standard and OSLO Premium may use a quicker method for carrying out vignetting analysis:

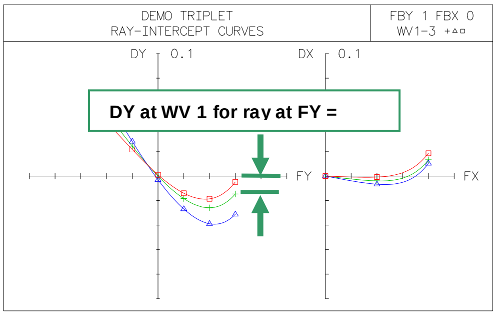
- From the **Optimize** menu header, select: **Support routines>Vignetting > Vignetting analysis**.
- Check **Copy vignetting data to field point set? No**
- Leave the **Maximum pupil position to test** at **5.0**
- Click on **OK**.

*VIGNETTING FACTORS

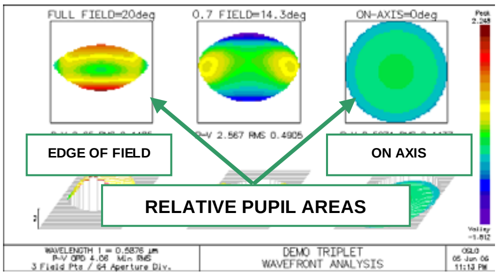
FPT	CFG	FBY	FBX	FY1	FY2	FXMAX
1	0	--	--	-1.040001	1.040001	1.040001
2	0	0.700000	--	-0.637293	0.810585	0.990811
3	0	1.000000	--	-0.431105	0.612924	0.901827

Graphical estimates

- From the **Evaluate** menu header select: **Ray fans > Single field point ...** and, leaving all the default values unchanged, click on **Set object point** at the foot of the spreadsheet.



- In the Set object point spreadsheet, set **Fractional coordinates of object point to FBY** = **1.00** **FBX** = **0.00** **FBZ** = **0.00.**
- Close both spreadsheets, and note from the graph that the value of the transverse ray aberration required is about -0.015 mm. (To confirm the units, from the **Lens** menu header, select: **Show operating conditions > General)**



- Click on the **Plot report graphics wavefront analysis** icon on the standard toolbar to get the pupil maps, and note that the area of the edge-of-field map is about 50% of the area of the on-axis map.

So we can conclude that the transverse ray aberration of the edge ray is about DY = -0.015 mm; the transmission at this field point is about 50%.

Numerical calculation

From the text window

- In the text window, trace the pupil ray (the ray through the centre of the aperture stop) from the edge of the object, by clicking on **Chf.**
- Then to trace a fan of rays in the meridional (Y) section, click on **Fan.** Set the **Minimum coordinate** to be **`-0.43,`** the **Maximum coordinate** to be **`0.61,`** and **Number of rays** to be **`2,`** and leave all other options as default values.
- Note the value of DY (transverse ray aberration in lens units) for the edge ray transmitted:

```
*TRACE FAN - FBY  1.00, FBX  0.00, FBZ  0.00
RAY      FY         FRAC RFS      DYA          DXA         DY           DX
  1    0.610000    0.530358   -0.071477       --       -0.013268       --
  2   -0.430000   -0.353777    0.052849       --        0.055365       --
```

- Click on **Spd** in the text window.
- Note the value of the per cent weighted ray transmission:

```
*SPOT DIAGRAM - FBY  1.00, FBX  0.00, FBZ  0.00 - POLYCHROMATIC
 APDIV    17.030000
 WAV WEIGHTS:
       WW1         WW2         WW3
    1.000000    1.000000    1.000000
 NUMBER OF RAYS TRACED:
       WV1         WV2         WV3
       104         104         104
 PER CENT WEIGHTED RAY TRANSMISSION:    44.827586

*SPOT SIZES
   GEO RMS Y    GEO RMS X    GEO RMS R   DIFFR LIMIT     CENTY        CENTX
    0.021401     0.007555     0.022696    0.003426   -0.002879        --

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD      RMS OPD   STREHL RATIO    RSY          RSX          RSZ
    2.224692     0.485250     0.091087   -0.004210       --           --
```

The conclusion then is that the transverse ray aberration of the edge ray is:

DY = -0.013268 mm,

and the transmission at this field point is:

44.8%

of the on-axis value, excluding the transmittances of optical materials and coatings.

From the menu headers

- From the **Evaluate** menu header select: **Ray fans > Single field point ...** and choose the **Command: Print Y ray-fan**.

- Set **Minimum fractional y-component of pupil coordinate** (FY) = **-.43**, and **Maximum fractional y-component of pupil coordinate** (FY) = **+.61**. Set the **Number of rays in fan** to the minimum value of **3.**

- Leaving all the other default values unchanged, do not close the dialog box, but click on **Set object point** at the foot of the spreadsheet.
- In the Set object point spreadsheet, leave the specification as **Direct entry** Set **Fractional coordinates of object point to FBY** = **1.00** **FBX** = **0.00** **FBZ** = **0.00.**
- Close the Set object point spreadsheet with the green tick, and click on OK in the Trace fans of rays through lens dialog box:

```
*TRACE FAN - FBY  1.00, FBX  0.00, FBZ  0.00
RAY       FY         FRAC RFS      DYA         DXA         DY          DX         DZ
  1     0.610000     0.530358   -0.071477      --      -0.013268       --         --
  2     0.090000     0.075914   -0.010854      --      -0.009257       --         --
  3    -0.430000    -0.353777    0.052849      --       0.055365       --         --
```

- From the **Evaluate** menu header select: **Spot diagram > Single spot diagram...**
- Select **Spot diagram Data** and click on **OK** (the earlier Set Object Point command is still valid).

```
*SPOT DIAGRAM - FBY  1.00, FBX  0.00, FBZ  0.00 - POLYCHROMATIC
 APDIV    17.030000
 WAV WEIGHTS:
       WW1         WW2         WW3
    1.000000    1.000000    1.000000
 NUMBER OF RAYS TRACED:
       WV1         WV2         WV3
  104.000000  104.000000  104.000000
 PER CENT WEIGHTED RAY TRANSMISSION:    44.827586
 SPOT DIAGRAM SYMMETRY:      1.000000
```

From the command line (abbreviated)

- In the command line, type the following:

  sop 1 0 0;trf y 2 -.43 .61;spd 200

  and click on the green tick, or press **Enter** on the keyboard.

```
*SET OBJECT POINT
         FBY          FBX          FBZ
       1.000000       --           --
        FYRF         FXRF          FY           FX
         --           --           --           --
         YC           XC          YFS          XFS          OPL     REF SPH RAD
      18.264293       --       -0.911383    -0.096417    65.421390    61.550663
*TRACE FAN - FBY  1.00, FBX  0.00, FBZ  0.00
RAY      FY         FRAC RFS      DYA          DXA          DY           DX
  1    0.610000    0.530358    -0.071477       --       -0.013268       --
  2   -0.430000   -0.353777     0.052849       --        0.055365       --

*SPOT DIAGRAM - FBY  1.00, FBX  0.00, FBZ  0.00 - POLYCHROMATIC
 APDIV    200.000000
 WAV WEIGHTS:
       WW1          WW2          WW3
    1.000000     1.000000     1.000000
 NUMBER OF RAYS TRACED:
       WV1          WV2          WV3
      13820        13712        13868
 PER CENT WEIGHTED RAY TRANSMISSION:    43.909889

*SPOT SIZES
   GEO RMS Y    GEO RMS X    GEO RMS R   DIFFR LIMIT     CENTY        CENTX
    0.020881     0.006382     0.021835     0.003276    -0.003196       --

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD      RMS OPD   STREHL RATIO     RSY          RSX          RSZ
    2.711822     0.447068     0.060859    -0.005045       --           --
```

The new value for the transmission (43.9%) is more accurate than the earlier result since a finer grid of rays (200 rings, not 17.03, in the pupil) was defined by the **spd** command.

By executing in the Edit window

- From the **Window** menu header select: **Editor > Open** or click the icon.
- Use the history button to call up the last line executed:

sop 1 0 0;trf y 2 -.43 .61;spd 200

- Copy and paste it into the Text editor window.
- Highlight it with the cursor (or press **Ctrl-A**), and press **Ctrl-E.** Results are the same.

From the command line (in full)

- In the command line, one might perhaps type the following:

```
set_object_point(1.0,0.0,0.0,0.0,0.0,1)
trace_fan(y,2,-0.43,0.61)
spot_diagram(chr,none,200)
```

These forms of the commands are used to make programs self-documenting. The short forms are more useful for command line entry.

The spreadsheet buffer

The spreadsheet buffer is an array of numerical storage cells, with 1999 rows numbered as in Microsoft Excel, which underlies each text window. The spreadsheet buffer is used for conveying the results of numerical OSLO calculations to variables in CCL commands, so it is important to understand how it works.

Clearing the text window and spreadsheet buffer

There are three ways to do this:

- EITHER right click anywhere in the text window and select **Clear window and SS buffer**
- OR, from the **Window** menu header, select: **Text > Reset.**
- OR, in the command line, Enter `twr` (or `textwin_reset`)

To clear the spreadsheet buffer *without* affecting the printed output in the text window:

- In the command line, enter `sbr` (or `ssbuf_reset`)

Reading from the spreadsheet buffer

- In the text editor window, change the first entry so the whole line looks like this:
  `sbr;sop 1 0 0;trf y 2 -.43 .61;spd 200`
- Highlight the line with the cursor, and press **Ctrl-E.**
- Watching the message area under the command line, click on the text window output to confirm the following spreadsheet cell allocations:

```
*SET OBJECT POINT
          FBY          FBX          FBZ
       [  a1  ]     [  b1  ]     [  c1  ]
         FYRF         FXRF          FY          FX
       [  a2  ]     [  b2  ]     [  c2  ]    [  d2  ]
          YC           XC          YFS         XFS          OPL      REF SPH RAD
       [  a3  ]     [  b3  ]     [  c3  ]    [  d3  ]    [  e3  ]    [  f3  ]

*TRACE FAN - FBY  1.00, FBX  0.00, FBZ  0.00
RAY       FY         FRAC RFS       DYA          DXA          DY          DX
  1    [  a4  ]     [  b4  ]     [  c4  ]    [  d4  ]    [  e4  ]    [  f4  ]
  2    [  a5  ]     [  b5  ]     [  c5  ]    [  d5  ]    [  e5  ]    [  f5  ]

*SPOT DIAGRAM - FBY  1.00, FBX  0.00, FBZ  0.00 - POLYCHROMATIC
 APDIV [  a6  ]
 WAV WEIGHTS:
        WW1          WW2          WW3
     [  a7  ]     [  b7  ]     [  c7  ]
 NUMBER OF RAYS TRACED:
        WV1          WV2          WV3
      13820        13712        13868
 PER CENT WEIGHTED RAY TRANSMISSION:    [  a8  ]

*SPOT SIZES
   GEO RMS Y    GEO RMS X    GEO RMS R  DIFFR LIMIT      CENTY        CENTX
     [  a9  ]     [  b9  ]     [  c9  ]    [  d9  ]    [  e9  ]    [  f9  ]

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD      RMS OPD   STREHL RATIO    RSY          RSX          RSZ
     [  a10  ]    [  b10 ]     [  c10 ]    [  d10 ]    [  e10 ]    [  f10 ]
```

Note that integers and headers are not included in the spreadsheet buffer.

- Click on the two numerical results indicated, and note the cell coordinates and values given in the message area as follows:

e4 = -0.0132683238458

a8 = 43.909889270714

Note also that these results are full precision (to 14 digits).

Writing to the spreadsheet buffer

- In the text editor window, add the command for formatted printing:

```
aprintf("DY = % 6.6f Trans = %4.1f %%\n",e4,a8)
```

giving the following output:

```
DY = -0.013268 Trans = 43.9 %
```

Note that the contents of cells of the spreadsheet buffer can also be accessed using the real array **ssb(row, column)**. For example, **e4** becomes **ssb(4,5)** and **a8** becomes **ssb(8,1)**.

The command **aprintf** places the two values in the spreadsheet buffer, still at full precision, even though they are printed with fewer places (6 and 1 respectively) after the decimal point. Note in particular that the cells are filled even if printing is turned off.

- Click on these results to confirm this:

a11 = -0.0132683238458
b11 = 43.909889270714

Scrolling the spreadsheet buffer

This section should be omitted at the first reading, as it describes a feature used only in advanced programming.

- Type in the command line: **sbrow** and press **Enter**

Result = 12

This is the row number of the next row to be written to in the spreadsheet buffer. The command **sbr (ssbuf_reset)** remaps the spreadsheet row whose number is the first argument, with the row number of the second argument. So to renumber the lines so that any new output is written to row 1 rather than row 12:

- In the text editor window, change the first entry so the whole line looks like this: **sbr 12 1;sop 1 0 0;trf y 2 -.43 .61;spd 200**
- Highlight it with the cursor, and press **Ctrl-E.**

Note that the row numbers are the same as before, but this time the rows which had been previously written are preserved, and numbered up to 1999.

We can restore the line numbering by using the **sbr** command with a negative index:

- In the command line type: **sbr -12 0**

Initial row numbering	a-column Values	After sbr 12 1	After sbr -12 0
1	1.000	1989	1
2	0.000	1990	2
3	18.264	1991	3
4	0.61	1992	4
5	-0.43	1993	5
6	200.0	1994	6
7	1.000	1995	7
8	43.9	1996	8
9	.02088	1997	9
10	2.71	1998	10
11	-0.013268	1999	11
12*		1*	12*
13		2	13

The effect of this is illustrated in the table. The next row to be written to (in other words, the value of the read-only variable **sbrow**) is marked with an asterisk in each case.

Chapter 7 - Slider-wheel design

1:1 wide angle relay

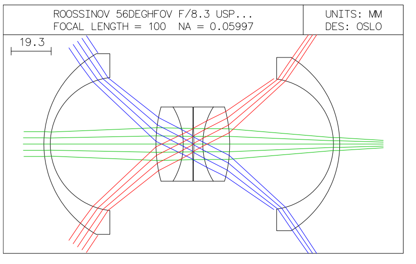
Introduction

The slider-wheel facility is a powerful tool, which allows the user to control any system variable while watching its effect on any numeric parameter or graphic display. In this chapter there will be an illustration of how slider-wheels alone can be used to complete a design task.

The requirement is for a four-element unity magnification relay. The object has a diagonal of 600 mm. The object to image distance is 451 mm. The distortion must be less than 0.1% and the design criterion is that the lowest value over the field of the modulation transfer function at 1.0 cycles/mm must be greater than 0.4. The wavelengths to be used for the MTF calculation are the usual three (0.58756 µm, 0.48613 µm and 0.65627 µm), weighted equally.

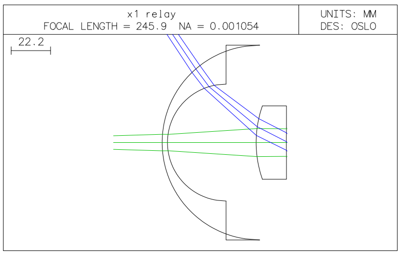
Defining the starting point

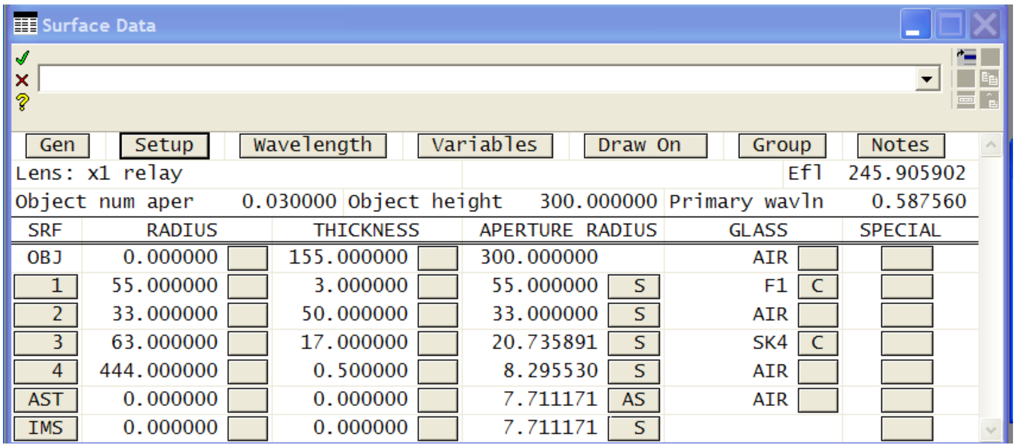
Clearly a symmetrical design is called for. In the public lens database (***OSLO Standard and Premium only***) there is an objective lens designed by Roossinov which will be used as the basis for the design of a relay lens. This has the title ROOSSINOV 56DEGHFOV F/8.3 USP2,516,724. It is nearly symmetrical and it has 13 surfaces. The design below has been adapted and simplified from this for use with all versions of OSLO.



Setting up the starting lens

- From the menu select **File**>**New lens** and choose a custom lens with 5 surfaces.
- In the surface data spreadsheet, change the lens title to **`x1 relay`**.
- Click on the gray button under **Aperture Radius** for surface 5, and select **Aperture Stop (A)** to move the aperture stop to surface 5.
- Fill in the lens parameters as shown in the diagram below. The values for **Aperture Radius** may be omitted, as these will be adjusted using aperture radius solves - that is to say, the aperture will be set at the value equal to the arithmetical sum of the paraxial marginal and pupil ray heights. This is such an extreme field angle lens that the results look unrealistic at first, but this can be corrected later.




Surface Data

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

Lens: x1 relay — Efl 245.905902

Object num aper 0.030000 Object height 300.000000 Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000	155.000000	300.000000		AIR		
1	55.000000	3.000000	55.000000	S	F1	C	
2	33.000000	50.000000	33.000000	S	AIR		
3	63.000000	17.000000	20.735891	S	SK4	C	
4	444.000000	0.500000	8.295530	S	AIR		
AST	0.000000	0.000000	7.711171	AS	AIR		
IMS	0.000000	0.000000	7.711171	S			

- In the Setup spreadsheet, enter the **Object NA** as **`0.03`** and the **Object height** as **`300`** mm. Close the Setup spreadsheet.

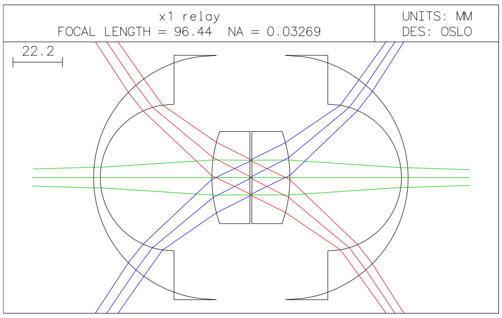
- Select surfaces 1 to 4, right click and choose **Copy.**
- Select surface 6 (IMS), right click and select **Paste**
- Select surfaces 6 to 9, right click and choose **Reverse.**
- Change the thickness for surface 5 to **`0.5`** and for surface 9 to **`155`**.
- In the **Aperture radius** column some are already Solves. Change the remaining apertures (surfaces 6 to 9) to **Solve (S)** by setting them to zero.
- Under **Radius**, click on the gray button for surface 9, choose **Minus curvature pickup**, and on the prompt **Enter pickup source surface**, enter 1. Press **Enter** twice more. Define a similar minus curvature pickup for surface 8 from surface 2, for surface 7 from surface 3 and for surface 6 from surface 4.
- Enter the command **`ctg`** to list the lens with curvatures:

```
x*LENS DATA
x1 relay
 SRF     CURVATURE      THICKNESS    APERTURE RADIUS        GLASS   SPE   NOTE
 OBJ        --         155.000000    300.000000              AIR

  1       0.018182       3.000000     55.000000 S             F1 C
  2       0.030303      50.000000     33.000000 S            AIR

  3       0.015873      17.000000     20.735891 S            SK4 C
  4       0.002252       0.500000      8.295530 S            AIR

 AST        --           0.500000      7.775659 AS           AIR

  6      -0.002252 P    17.000000      8.294476 S            SK4 C
  7      -0.015873 P    50.000000     20.712585 S            AIR

  8      -0.030303 P     3.000000     33.000000 S             F1 C
  9      -0.018182 P   155.000000     55.000000 S            AIR
 IMS        --             --        300.541968 S
```

- Click on **Gen** in the Surface data spreadsheet to open the General conditions spreadsheet.

- Under **Ray aiming mode**, select **Wide angle mode.**
- Close the General conditions spreadsheet.
- Change the Lens drawing conditions to draw 3 rays for each of the field points FBY = 0, FBY = -1, FBY = +1.

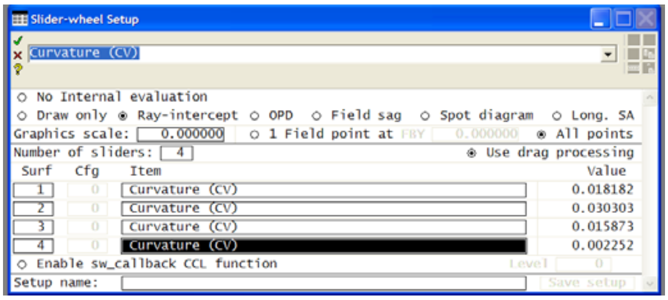
The lens drawing should now appear as shown in the diagram.



Slider-wheel design with ray intercept curves

- Open the Slider-wheel Setup spreadsheet by clicking on the icon in the main window toolbar.

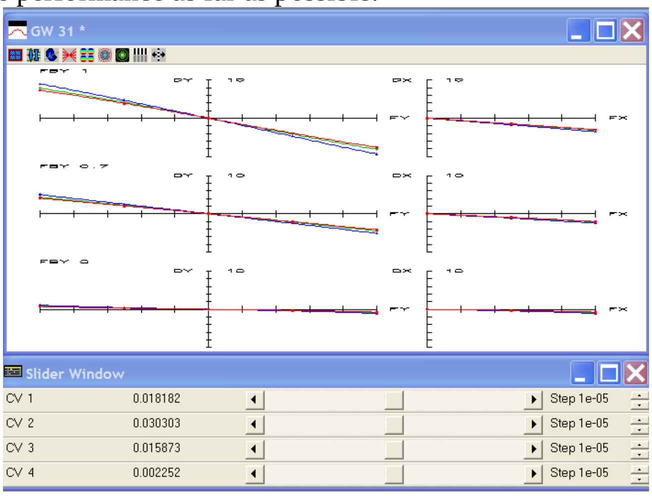
- Select **Ray-intercept**, **All points**, **Number of sliders = 4**, and define sliders on surfaces **1,2,3,4** for the curvature (**cv**).



- Close the Slider-wheel Setup spreadsheet.

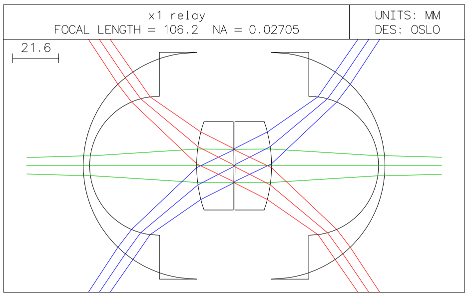
At this point the four sliders and two graphics windows, GW31 and GW 32 should become visible. If not, try using the Tile command, or open and close the Slider-wheel spreadsheet again.

- The default step size is too large. Click on the lower scroll button at the right-hand end of each slider-wheel to bring the **Step** to **1e-05**.
- Adjust the sliders to improve the performance as far as possible.
- Once the aberrations are too small to discern at the default aberration plotting scale, reopen the Slider-wheel Setup spreadsheet and close it again immediately. The aberrations will be redrawn with a new scale, and the slider-wheels re-centered in their tracks. The step size will still need to be changed, however.



- If a slider reaches the end-stop, change the step to re-center it. Note that the graphics zoom feature works on both windows, and the zoom settings are preserved during slider operation.

One possible solution, for example, is



CV 1 = 0.018822 (RD 1= 53.130 mm)

CV 2 = 0.030683 (RD 2 = 32.591mm)

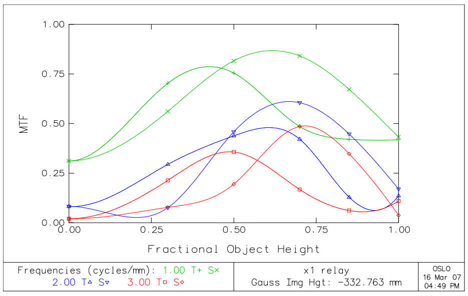
CV 3 = .015523 (RD 3 = 64.420 mm)

CV 4 = .002462 (RD 4 = 406.13 mm)

Plotting the MTF across the field

- From the **Evaluate** menu header select **Transfer Function > MTF vs field**
- Enter three frequencies in units of cycles per mm: **1.0, 2.0, and 3.0**.

This plots the modulation transfer function at all points in the field for the three spatial frequencies. In the example shown here, the upper (green) curve, which shhows the MTF at 1 cycle per mm, still falls well below the desired 0.4 level over part of the field of view.

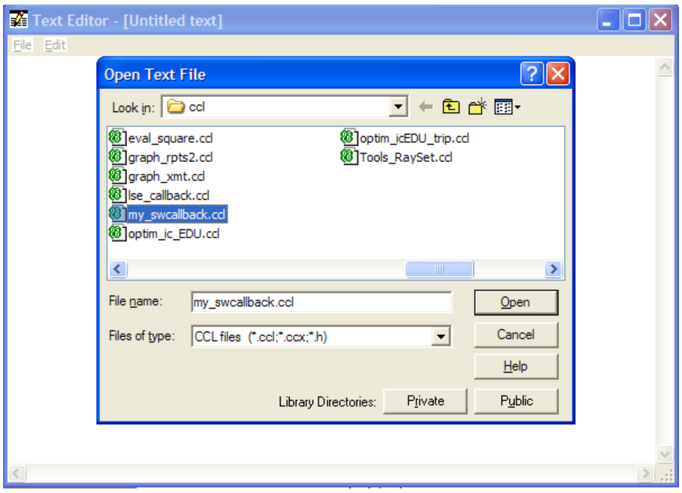


Editing the slider-wheel callback command

In order to use the slider-wheels to optimize the MTF across the whole field, it will be necessary first to make a small modification to one of the CCL commands in the /**private/ccl** directory. Some users may prefer to skip this exercise and return to it once the next chapter on programming has been covered.

- Open the text editor either by clicking on the icon, from the menu header **Window > Editor > Open** or typing the command **ewo.**

- In the Text editor window, click on **File** > **Open**.
- At the bottom of the window which opens, after **Library Directories:** click on **Private**.
- Of the files which have a green icon (*.ccl files) select **my_swcallback.ccl** and click on **Open**.



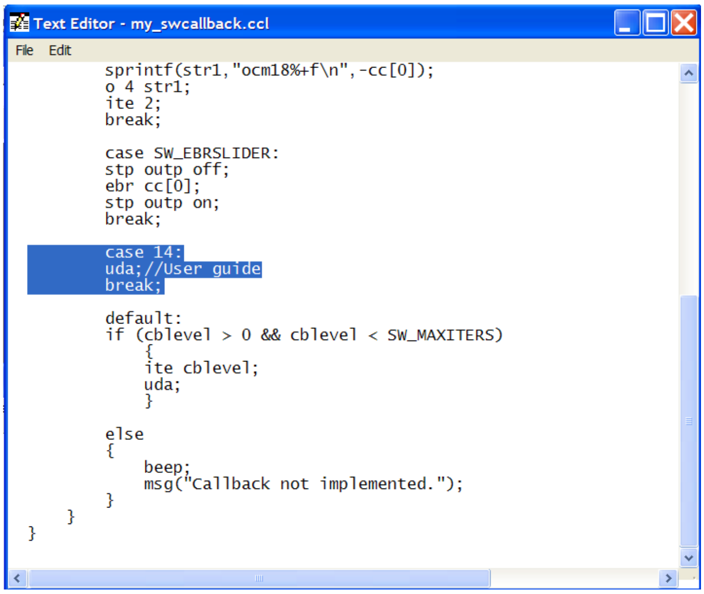
This file contains a single command

```
cmd Sw_callback(int cblevel, int item, int srf)
```

- Go to line 36 of the file (**Ctrl-G** or **Edit > Goto Line**, and enter **36**).
- After the last **break;** and before the line **default:** add the lines:

```
case 14:
uda;  // User guide
break;
```

When typing this entry you must take care that the first line ends with a colon (**:**), and the second and the third with a semicolon (**;**). On the second line anything following the **//** is treated as a comment.



- In the text editor window (not the main window) click on **File** > **Save**. Compilation should be automatic, and the message in the text window should be:

***CCL COMPILATION MESSAGES:** **No errors detected**

To explain, if the slider-wheel callback CCL is enabled by the user, then the command **Sw_callback** is called whenever a slider-wheel is moved. When this happens, the value of the integer argument called **Level** is passed to the CCL command, where it appears as the integer **cblevel**. This determines which action to be taken by the callback command.

If the **sw_callback CCL function** is invoked with a value of **Level** between 1 and 9, that number of cycles of optimization (iterations) is performed. If **Level** is 11, then the slider-wheel controls field angle, and if **Level** is 13 it controls entrance beam radius. The option **Level** = 13 is used in one of the tutorials.

As a result of the change, if the **sw_callback CCL function** is invoked with a value of **Level** equal to 14, then a single command **uda** will be executed. This command (**update_all** in long form) has the effect of updating the graphics in all open updateable windows (i.e. those marked UW).

All this occurs within the switch statement, with different outcomes according to the value of **cblevel**, the switch parameter.

The listing of the modified CCL command is given below.

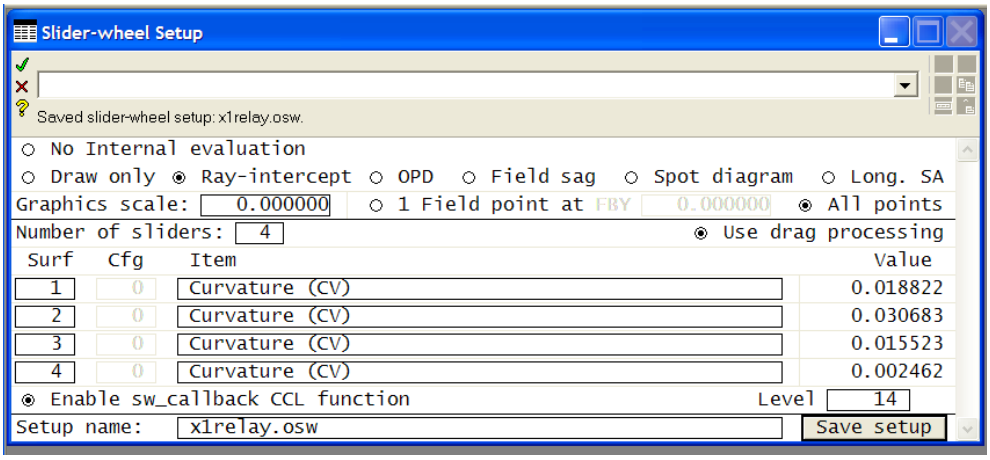
Listing of the modified slider-wheel callback CCL

```
/************************************************************************************
*  This file contains some simple callbacks that are used in the documentation examples  *
*  with slider-wheel windows. It is meant to be extended by users as needs arise. The    *
*  callback uses the "cblevel" parameter to designate a particular action. The user then *
*  enters the appropriate number in the Slider-wheel Setup window in the cell marked     *
*  "Level". The value of "Level" is passed to this command as "cblevel" and determines   *
*  the task to be performed.                                                             *
*************************************************************************************/

#define SW_MAXITERS           10
#define SW_ANGSLIDER          11
#define SW_DIFFRACTDBLT       12
#define SW_EBRSLIDER          13

cmd Sw_callback(int cblevel, int item, int srf)
{
       switch (cblevel)
       {
              case SW_ANGSLIDER:
              stp outp off;
              ang cc[0];
              stp outp on;
              break;

              case SW_DIFFRACTDBLT:
              sprintf(str1,"ocm18%+f\n",-cc[0]);
              o 4 str1;
              ite 2;
              break;

              case SW_EBRSLIDER:
              stp outp off;
              ebr cc[0];
              stp outp on;
              break;

              case 14:
              uda;//User guide
              break;

              default:
              if (cblevel > 0 && cblevel < SW_MAXITERS)
                     {
                     ite cblevel;
                     uda;
                     }

              else
              {
                     beep;
                     msg("Callback not implemented.");
              }
       }
}...
```

Slider-wheel design using MTF at one frequency

- Plot the MTF curves at the spatial frequencies of 1, 2, and 3 cycles/mm as before.
- Open the slider-wheel spreadsheet.

- Set up the slider-wheels as before, but this time click on **Enable sw_callback CCL function.**
- Enter **Level** as **14**.
- Enter the **Setup name** **x1_relay** and click on the **Save setup** button.



This slider-wheel setup (the slider wheel definitions and the other data) is now saved in a file **x1_relay.osw**, which is stored in the directory **.../private/bin/osw/**

- Close the slider-wheel setup spreadsheet.
- On each slider-wheel change the step size to 1e-05 as before (these values are not stored in the slider-wheel data).
- Adjust the curvatures to maximize the MTF at 1 cycle/mm over the whole field.

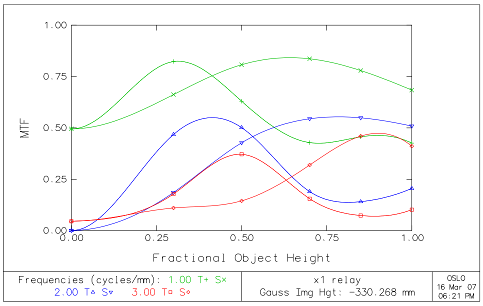
One possible solution, illustrated here, is:

CV 1 = 0.01778 (RD 1= 56.237 mm)

CV 2 = 0.03090 (RD 2 = 32.359 mm)

CV 3 = .01585 (RD 3 = 63.079 mm)

CV 4 = .002312 (RD 4 = 432.48 mm)

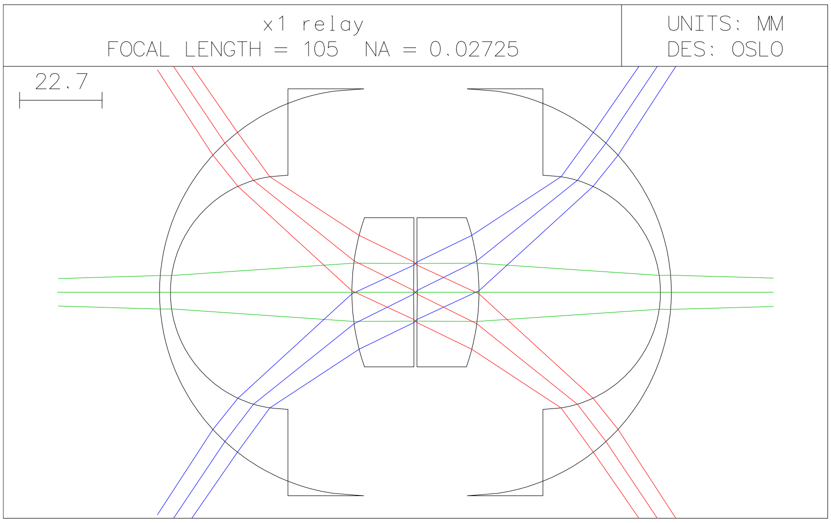


The smallest MTF value for this design is 0.42. This completes the design ask.

This example illustrates in microcosm how even a problem with clearly defined objectives and only 4 variables can have a large number of solutions, all meeting the requirements but differing in subtle ways.

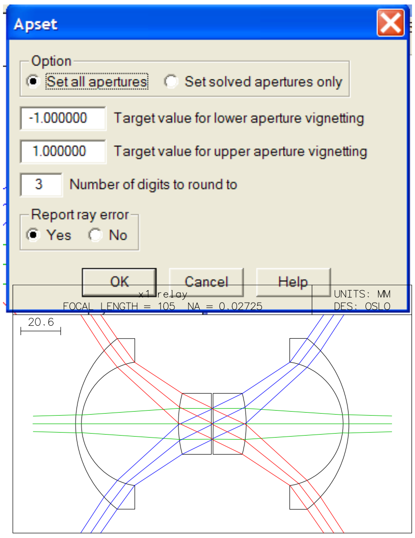
Setting clear apertures

The apertures at present are based on paraxial ray "solves." To complete the design, the clear aperture values must be set in accord with real ray, not paraxial ray, requirements.



- From the **Optimize** menu header select **Support routines > Vignetting > Set apertures.**

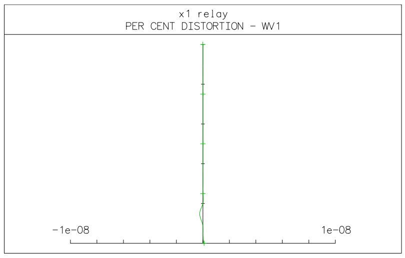
- Leaving all the choices as defaults, click on **OK**.




```
*APERTURES
 SRF   TYPE APERTURE RADIUS
  0     SPC   300.000000
  1     SPC    44.200000
  2     SPC    32.000000
  3     SPC    15.800000
  4     SPC     8.360000
  5     SPC     7.950000   CHK
  6     SPC     8.360000
  7     SPC    15.800000
  8     SPC    32.000000
  9     SPC    44.300000
 10     CMP   300.550935
```

- If the slider-wheel spreadsheet is re-opened after the lens is saved, the previous setup will have been deleted from it. It can be retrieved by clicking in the **Setup name** window and right-clicking on **x1_relay.osw** from the list presented.

- Finally, enter the command **`pld mon`** to confirm that the level of distortion in the design is indeed very low.

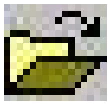


Chapter 8 - Programming

Introduction

This chapter will include the basics of how to create a new command producing textual output, and how to include that command as one of the options in the text window header menu. Next there will be how to create a new graphics command, and how to create an icon for this in one of the graphics window headers. Finally there will be a brief review of the SCP and CMD languages.

To illustrate these, it is helpful to have a standard lens in storage.



- Click on the icon for **Open an existing lens**. If the warning message appears **... Save changes to current lens file?** Click on **No.**
- At the bottom of the window which opens, after **Library Directories:** click on **Public**.
- Select **demo > edu** and then click on **demotrip.len**.
- Click on **Open**.

Defining a new command: sno

In the surface data spreadsheet, the button labeled **Notes** gives access to the first 5 lines of the user-defined commentary which is stored with each lens. This consists of up to 10 lines, but the 6th is reserved for some optimization parameters, and the 10th for the public database lens class.

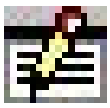
The standard OSLO command for listing the system notes is **opc sno.** There is no facility for calling this from the text window toolbar. This section shows how a new command, **sno**, which lists the system notes, can be written. Then the procedure for adding a label **Sno** to the text window (Standard Tools) toolbar will be given, so that the system notes (up to 10 lines of documentation stored with each lens) can be listed with a single click.

- First, try out the command from the keyboard. Type the command **opc sno**

```
*CONDITIONS: SYSTEM NOTES
1: This Cooke triplet is used throughout the OSLO documentation as an example.
2: It is a minor variation on a lens designed by hand by R. Kingslake (see "Lens
3: Design Fundamentals", pp286-295, Academic Press 1978, ISBN 0-12-408650-1), who
4: used nothing more than a hand calculator! The Cooke triplet was invented by
5: Dennis Taylor in 1893, and is still very widely used as a low-cost objective.
10: COOKE TRIPLET
```

CCL commands are stored in ASCII, and may be created either using the OSLO standard text editor or using Notepad++®. Only the use of the first will be described in this chapter.

To create the new command:

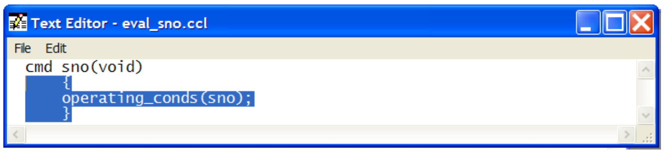


- If the icon for **Open the standard text editor** appears on the main window taskbar, click on it. Otherwise from the **Window** menu header select **Editor > Open.** Alternatively type the command **ewo** in the command line,

- In the editor window, select **File > New** and type:

```
cmd sno(void)
    {
    operating_conds(sno);
    }
```

Note that there is no punctuation after **(void)**, and there is a semicolon (**;**) after the single line command.



- Highlight the last three lines with the cursor and press **Ctrl-E** to check that the program has been entered correctly.
- There are only two menu options in the editor window header. Choose **File > Save as... ,** click on the gray button labeled **Private** at the bottom, and choose **File type: CCL files (*.ccl,*.ccx,*.h).**
- Enter **File name** **eval_sno** and click on **Save.**
- Compilation takes place automatically:

```
*CCL COMPILATION MESSAGES:
 No errors detected
```

should be the message which appears in the text window.

- Enter the new command in the command line: **sno**
- In the text editor window, add the documentation as

```
//
// Written by [your name] [date]
//

cmd sno(void)

// hlp:  <P>SNO</P>
// hlp:  <P> Prints the system notes.</P>

     {
     operating_conds(sno);
     }
```

- In the editor window header, (*not* the main window) click on **File > Save.** The compilation message will appear again:

```
*CCL COMPILATION MESSAGES:
 No errors detected
```

Each command definition in the **private/ccl** directory must be unique, so do not attempt to save the command **sno** again in a ***.ccl** file of another name. The error message will be:

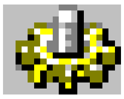
```
*CCL COMPILATION MESSAGES:
 eval_sno2.ccl 2: Duplicate procedure definition
```

and this error will persist until the duplicate procedure definition is removed.

Structure of a CCL command

CCL commands can be created by the user to automate sequences of actions, and to carry out calculations and plots specific to a user's requirements. They are stored as ASCII text in the directory **.../private/ccl** (not a sub-directory) and must be compiled before use.

The simplest CCL command can have the structure:



```
cmd command_name1()
     {
     OSLO_command1;
     OSLO_command2;
     ...etc...
     }
```

This is stored in a file **demo_anyfilename.ccl**. (Prefixes of user-written command files should ideally be restricted to **demo_, eval_, graph_** and **optim_**). It is compiled using the icon (or, in the case of OSLO EDU where the icon is not displayed) the menu sequence **Tools > Compile CCL >Private**, or the command `ccl`.

It is executed using the call:

```
command_name
```

For example, the CCL file containing the program;

```
cmd hallo(void)
     {
     printf("Hallo world\n");
     }
```

may be stored as **my_first.ccl**, compiled, and then called using the command:

```
hallo
```

This is described in detail in **Help > OSLO Help > Contents > Programming > CCL Programming > Using CCL.**

With formal parameters, or arguments, the structure of a CCL command might become:

```
real argument_name1;
int argument_name2;

cmd command_name(real argument_name1,int argument_name2)
     {
     OSLO_command1(argument_name1,argument_name2);
     OSLO_command2(argument_name1,argument_name2);
     }
```

This is compiled and then executed using (for example) either free format:

```
command_name 1.0 1
```

or the more formal version, often used within CCL code:

```
command_name(1.0,1);
```

In this case the two global variables `argument_name1` and `argument_name2` might be used by another CCL command.

Local variables may also be declared. Take, for example, the CCL command:

```
real argument_name1;
int argument_name2;

cmd command_name(real argument_name1,int argument_name2)
     {
     real local_variable1;
     int local_variable2;

     local_variable1=3.0;
     local_variable2=4;

print(argument_name1,argument_name2,local_variable1,loca
l_variable2);
     }
```

If this is called using the command

```
command_name 1.0 2
```

the output is:

```
1.000000   2   3.000000   4
```

Search CCL library: scanccl

Assume that **eval_sno.ccl** has been added to the **private\ccl** directory, as described above.

- From the menu header select **Tools > Search CCL library ...**
- Under **Directory to browse** select the option **Private**
- Select the default option **Sort functions by filename** and click on **OK.**

```
**   8 functions are defined in the private directory:**
** C:\Program Files\OSLO\EDU64\private/ccl/

TYPE          FCTN NAME   ARGUMENTS LINE DEFINITION FILE
----          ---------   --------- ---- ---------------
cmd           sno                      5 eval_sno.ccl
cmd           sw_callback             15 my_swcallback.ccl
                          int    cblevel
                          int    item
                          int    srf
cmd           tlex_1                  18 dbtutorial.ccl
                          real   tl__radius1
                          real   tl__radius2
                          real   tl__refractive_index
```

The new command **sno** appears as the first entry in the list of function names; also given are the number of lines in the command, and the name of the file in which it was defined.

Defining a new command: ctn

The next new CCL command is an extension of one which appeared in chapter 3.

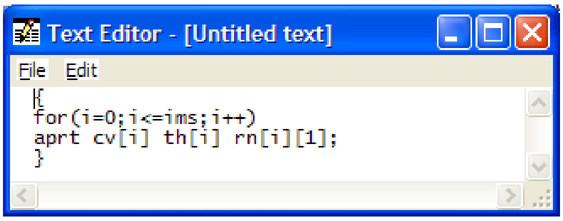
Initial version of command

- From the **Window** menu header select: **Editor > Open**, or type the command **ewo** in the command line, or click on the main window toolbar icon.

- Type in the following line:

```
for(i=0;i<=ims;i++)aprt cv[i] th[i] rn[i][1];
```

- Split it into two lines and surround with curly brackets.

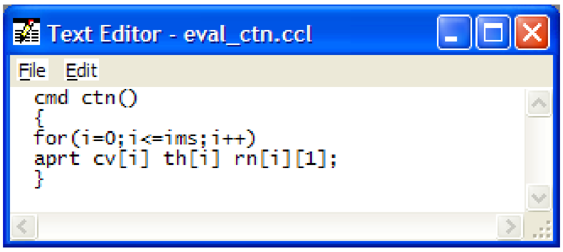


- Highlight the whole window (**Ctrl-A**) and execute (**Ctrl-E**).
  The following appears in the active text window:

```
       --     1.0000e+20    1.000000
 0.047059       2.000000    1.620410
-0.006303       6.000000    1.000000
-0.049383       1.000000    1.616592
 0.051813       6.000000    1.000000
 0.007080       2.000000    1.620410
-0.057854      42.950000    1.000000
       --             --    1.000000
```

- Add a line at the beginning:

```
cmd ctn()
```



- In the Text Editor window click on **File > Save as...**
- Ensure first that the bottom window reads **Save as type: CCL files.**
- Click on Library Directories **Private**.
- For **File name** type `eval_ctn`
- Click on **Save**.
- Look in the text window. There should be a message

```
*CCL COMPILATION MESSAGES:
 No errors detected
```

  If the message appears:

```
*CCL COMPILATION MESSAGES:
eval_ctn.ccl 2: Duplicate procedure definition
```

then there is already a file with extension .ccl in the private/ccl directory containing the line `cmd ctn()`Locate it and delete it, or change its extension to .ccx. It may be impossible to do this if file extensions are hidden. If so, it is necessary to change the Windows file viewing settings. Under My Computer > Tools > Folder options > View tab > Advanced Settings > Hide extensions for known file types: Uncheck.

If there is another compilation error, check the listing carefully, especially the one semicolon and the three different types of bracket:

```
cmd ctn()
{
for(i=0;i<=ims;i++)
aprt cv[i] th[i] rn[i][1];
}
```

Extra lines and spaces are not a problem.

- Once compilation is successful, in the command line enter `ctn.` The output should be as before.

Version with formatted output

- Change the `aprt` print statement to:

```
aprintf("%3i %12.8f %9.4g %.6f\n",i,cv[i],th[i],rn[i][1]);
```

Here, each format specification begins with a % sign:

The format specifier %3i requires that the integer i is to be printed with a field width of 3, right justified within this width.

The format %12.8f gives a minimum field width for cv[i] of 12 characters, with 8 digits printed after the decimal point.

The format %9.4g prints th[i] in decimal notation with 4 significant figures, but in exponential form if it is 10000 or more, or less than 0.00001.

The format %.6f requires n[i] to be printed with 6 digits after the decimal point, and no minimum field width.

- Save and execute, giving:

```
 0   0.00000000    1e+20 1.000000
 1   0.04705882        2 1.620410
 2  -0.00630318        6 1.000000
 3  -0.04938272        1 1.616592
 4   0.05181347        6 1.000000
 5   0.00707965        2 1.620410
 6  -0.05785363    42.95 1.000000
```

Adding the glass name string

Glass name strings are not directly accessible. However, the command **get_glass_name(i)** copies the name of the glass for the *i*th surface into a read-only string **glass_name** (See under **Help > OSLO Help > Contents > Programming > Accessing Data > Other Data > Data Functions).**

- Add an extra pair of curly brackets after the **for** statement, and insert:

```
get_glass_name(i);
```

- Change the print statement to (on a single line):

```
aprintf("%3i %12.8f %9.4g %.8s %.6f\n"
                           ,i,cv[i],th[i],glass_name,rn[i][1]);
```

The format %.8s requires the glass_name string to be printed with a maximum of 8 characters.

- List the complete command:

```
cmd ctn()
   {
   print(" SRF       CV       TH     GLASS       RN");
   for(i=0;i<=ims;i++)
      {
      get_glass_name(i);
      aprintf("%3i %12.8f %9.4g %.8s %.6f\n",i,cv[i],th[i],glass_name,rn[i][1]);
      }

   }
```

Adding headers and documentation

The following conventions have been established by previous writers of OSLO macros, and they are worth observing:

1. Each CCL file opens with a set of three or more comment lines giving the author, date, and any update information. e.g.

```
//
// Written by [Your initials] [Date]
//
```

2. All documentation for a CCL command is given in HTML format between the header and the body, commented out and preceded by hlp. For example:

```
// hlp:  <P>Lists curvature, thickness, glass type and refractive index.</P>
```

3. No default system variables are ever used, so that, for example, the command sequence

```
i=92;ctn;prt i
```

must always give the same result. So declare all variables as local variables within the command: e.g.

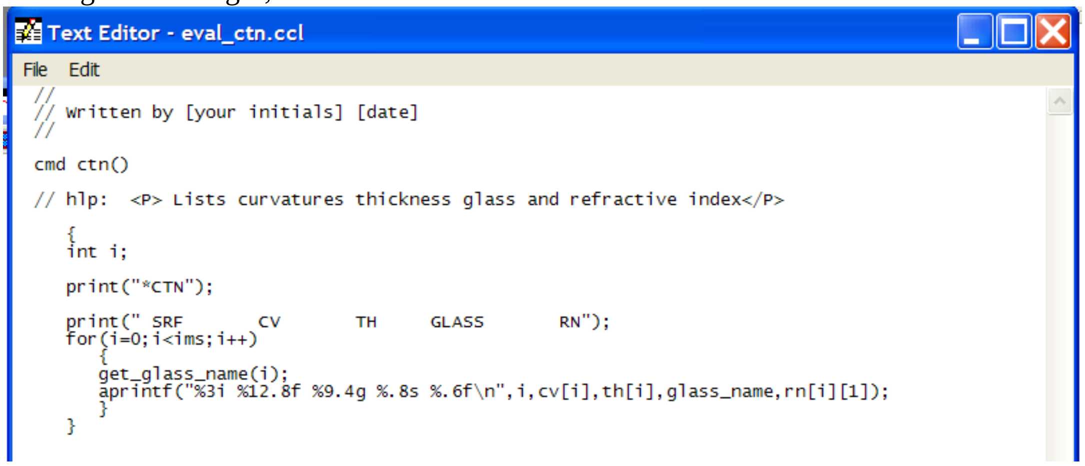
```
int i;
```

Of course these can have any name chosen arbitrarily, but by keeping to the default variable names, the **Ctrl-E** execution of selections of code within the text editor window can still proceed, provided the declaration `int i;` itself is not highlighted.

4. Commands which give just printed output are echoed, preceded by a star, in upper case. e.g.

```
print("*CTN");
```

Making these changes, the final version of the command becomes:



Text Editor - eval_ctn.ccl

File Edit

```
//
// Written by [your initials] [date]
//
cmd ctn()
// hlp:  <P> Lists curvatures thickness glass and refractive index</P>
  {
  int i;
  print("*CTN");
  print(" SRF        CV        TH      GLASS       RN");
  for(i=0;i<ims;i++)
     {
     get_glass_name(i);
     aprintf("%3i %12.8f %9.4g %.8s %.6f\n",i,cv[i],th[i],glass_name,rn[i][1]);
     }
  }
```

The output from a call of the command `ctn` is:

```
*CTN
 SRF        CV          TH     GLASS        RN
  0    0.00000000    1e+20  AIR       1.000000
  1    0.04705882         2 SK16       1.620410
  2   -0.00630318         6 AIR        1.000000
  3   -0.04938272         1 F4         1.616592
  4    0.05181347         6 AIR        1.000000
  5    0.00707965         2 SK16       1.620410
  6   -0.05785363     42.95 AIR        1.000000
```

The text window toolbar

Commands which generate only printed output are by convention placed in the text window toolbar. The format for a text window toolbar is:

```
menu toolbar_number
        {
        "Label,tooltip_label" = "command",
        "Label2,tooltip_label2" = "command2",
        }
```

where the first **Label** (by convention having only 3 or 4 letters) is what appears on the toolbar, the second, **tooltip_label**, is more detailed, and only appears in a cream-colored box when the cursor hovers over the first label. The **command** may be either CCL or OSLO command(s). The **toolbar_number** is **toolbar50** for the Standard Tools text window toolbar.

Adding the command <u>sno</u> to the toolbar

- Still in the Text Editor window, select **File > Open** and look in the Private CCL directory. Open the file **a_menu.ccl**.
- (If there is no file **private/ccl/a_menu.ccl**, open the file **/public/ccl/a_menu.ccl**, and save it as **private/ccl/a_menu.ccl**)
- Go to line 1339 of this file (**Ctrl-G** and enter **1339** in the dialog box). This should give the entries for:

```
menu toolbar50
```

- After the line:

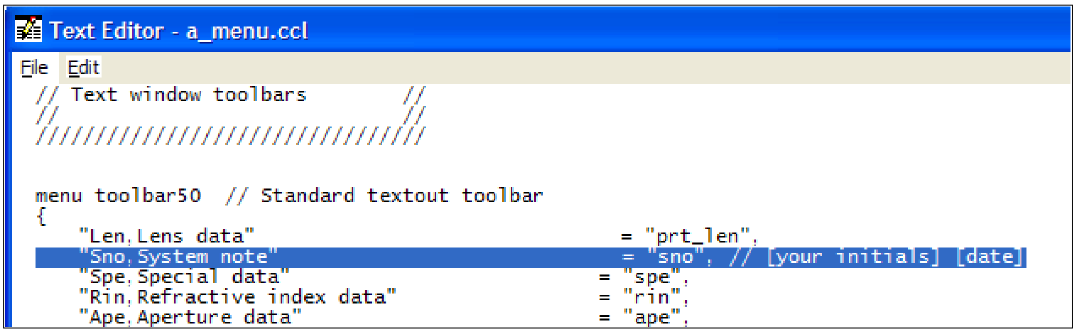
```
"Len,Lens data"                = "prt_len",
```

add the line (note the comma before the comment):

```
"Sno,System note"              = "sno",//[your initials][date]
```

- Compile again by saving the file:

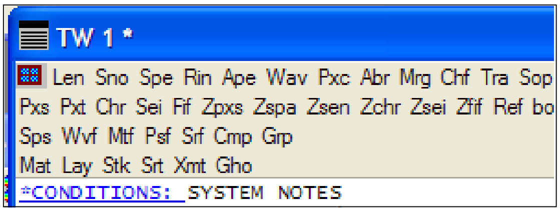
```
*CCL COMPILATION MESSAGES:
No errors detected
```



Calling sno from the toolbar

- Click on **Sno** in the text window toolbar. If it is not visible, ensure that the Standard Tools menu has been selected.

  Once again the output is:



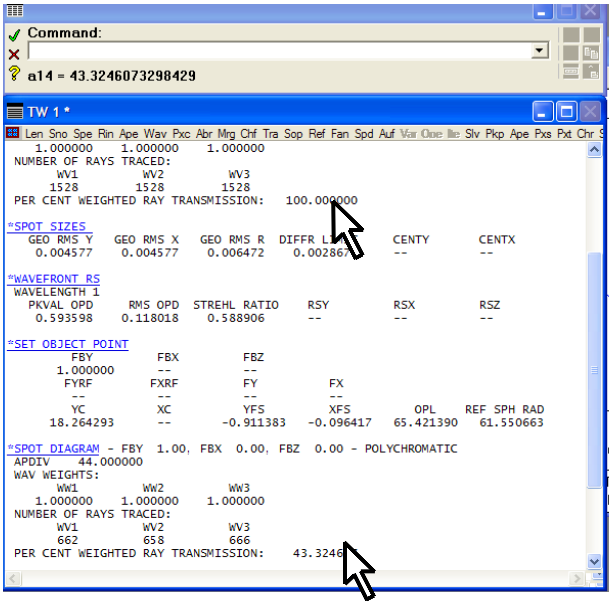

```
*CONDITIONS: SYSTEM NOTES
1: This Cooke triplet is used
throughout the OSLO documentation as
an example.
2: It is a minor variation on a lens designed by hand by R. Kingslake (see "Lens
3: Design Fundamentals", pp286-295, Academic Press 1978, ISBN 0-12-408650-1), who
4: used nothing more than a hand calculator! The Cooke triplet was invented by
5: Dennis Taylor in 1893, and is still very widely used as a low-cost objective.
10: COOKE TRIPLET
```

Defining a new command: xmt

In this exercise a command **xmt** will be created which plots a graph showing the transmission fal1-off across the field arising from vignetting. (The effect of coatings and of the internal transmission of optical materials, available in OSLO Premium, is not included in this analysis).

The command will be modified to prevent errors occurring when no rays are transmitted, or when the chief ray fails. This will demonstrate the use of an error handler.

Then a new icon will be created, and placed in the Spot Diagram menu of the graphics window toolbar to enable the new command to be called with a single click.



Writing a command xmt to print transmittance values

- Open the lens file **/public/demo/EDU/ demotrip.len**
- In the Text Editor window, open a new file and type the following in a single line:

  sbr;sop 0 0 0;spd 44;sop 1 0 0;spd 44

- Highlight with the cursor, press **Ctrl-E** and click on the two values of PERCENT WEIGHTED RAY TRANSMISSION (**100.00 and 43.324607**) which appear in the text window. Note the coordinates of the two spreadsheet cells (**a6, a14**).
- In the text editor, add a second line containing a print command.

  prt a6,a14;

- Highlight both lines and press **Ctrl-E** to confirm the correct values have been printed.

- The transmission curve is to be plotted at 50 points over a range of value of FBY from 0.0 to 1.0. Introducing the pre-defined integer i as a variable to count through these points, and we can generate all the results using a `for` loop:

```
sbr;
for(i=0;i<51;i++)
       {
       sop i*.02 0 0;
       spd 44;
       }
```

  To extract the relevant values from the spreadsheet, and print them as a neat table, we must switch off printed output with **`stp(outp,off)`** and extract the transmission values from the spreadsheet. The spreadsheet cell number of the transmission value of the *(i+1)th* field point is *a(6+8i)* or, as a CCL formula, **`ssb(6+8*i,1).`** Introducing the double precision predefined variables x (the value of FBY) and y (the % transmission), we can use these in a print statement to create the necessary table: **`prt x,y;`** This statement will produce visible output despite the fact that the preference **`stp(outp,off);`** has been called, provided **`prt`** and not **`aprt`** is used for printing.
  Predefined variables are used at this stage because the **Ctrl-E** compilation method is incompatible with either local or global variables.

- So change the program to:

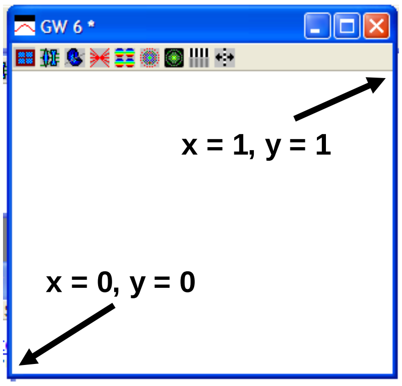
```
stp(outp,off);
sbr;
for(i=0;i<51;i++)
       {
       x=i*0.02;
       sop(x,0,0);
       spd(44);
       y=ssb(6+8*i,1);
       prt(x,y);
       }
stp(outp,on);
```

- Highlight it all and execute with **Ctrl-E** to generate the entire list of 51 values giving the percentage transmission across the field:

```
  --      100.000000
0.020000  100.000000
0.040000  100.000000
...etc
0.960000   47.120419
0.980000   45.811518
1.000000   43.324607
```

Converting xmt printed output to graphics

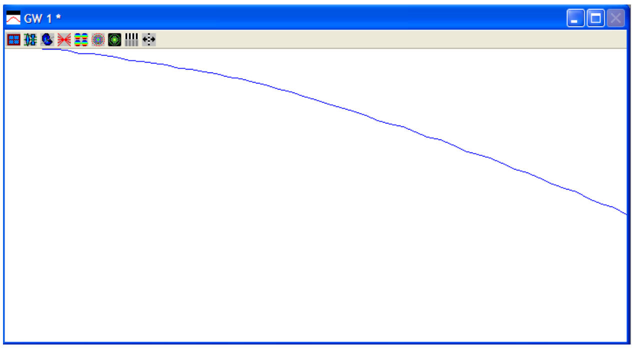
The text window spreadsheet is used as the vehicle for transferring the printed data into plot commands.



- At the beginning, add the command **`gwr;`** (graphic window reset) to clear the window and define the dimensions of the plot area to be in the range x=0 ... 1, y = 0 ... 1.
- Also before the first calculation, add the plot command, **`moveto(0,1)-`** most lenses will have 100% transmission on axis.

- Add **pen(3)** to plot in dark blue.
- Delete the print statement.
- Insert the main plot command, **lineto(x,y/100);** where the /100 scales the y-values to keep them within the range 0 ... 1.
- At the end, add **gshow;** to ensure that the plot output is drawn immediately and not held in a buffer. It may still be necessary to click on the window to have the graph drawn in full.

```
stp(outp,off);
sbr;
gwr;
moveto(0,1);
pen(3);
for(i=0;i<51;i++)
        {
        x=i*0.02;
        sop(x,0,0);
        spd(44);
        y=ssb(6+8*i,1);
        lineto(x,y/100);
        }
stp(outp,on);
gshow;
```



Preserving the text window contents

- In the second line, replace the `sbr` command by the two lines:

```
k=sbrow;
sbr(k,1);
```

- On the third last line, insert the line:

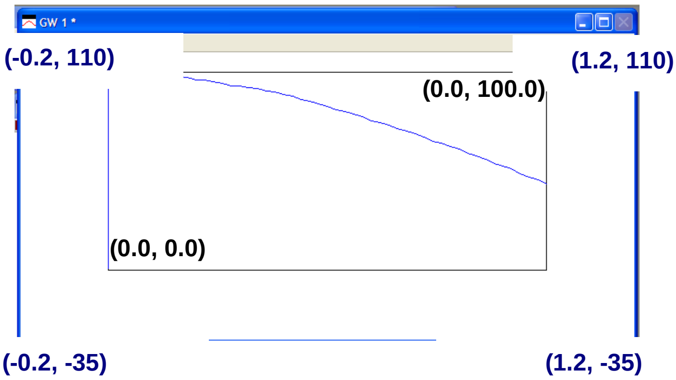
```
sbr(-k,0);
```

Here **k**, a predefined integer variable, has been used to keep the value of **sbrow**, the index of the first unwritten row of the spreadsheet.

Scaling and drawing the axes

- After the **gwr** command, add the following commands to re-scale the window as illustrated in the diagram, and to draw the axes around the graph: .

```
window(-0.2,1.2,-35,110);
moveto(0,0);
lineto(1,0);
lineto(1,100);
lineto(0,100);
lineto(0,0);
```



- Also change the lineto command to **lineto(x,y)** to cover the new range of y from 0 to 100.
- Finally surround the whole procedure with curly brackets, add the line **cmd xmt()** at the top, and save in file **private/ccl/graph_xmt.ccl**.

- Note that up to this point only predefined variables have been used (integers `i,k` double precision real `x,y`). Thus it is possible to highlight and execute part of, or the whole command (*excluding* the `cmd xmt()` header itself) using **Ctrl-E.** This is helpful for locating errors.

The listing of the command is as follows:

```
cmd xmt()

   {
   stp(outp,off);
   k=sbrow;
   sbr(k,1);
   gwr;

   window(-0.2,1.2,-35,110);
   moveto(0,0);
   lineto(1,0);
   lineto(1,100);
   lineto(0,100);
   lineto(0,0);

   moveto(0,100);
   pen(3);
   for(i=0;i<51;i++)
      {
      x=i*0.02;
      sop(x,0,0);
      spd(44);
      y=ssb(6+8*i,1);
      lineto(x,y);
      }
   sbr(-k,0);
   stp(outp,on);
   gshow;
  }
```

Adding standard plot commands to xmt

- Add the pre-processor command at the top of the file:

```
#include "../../public/ccl/inc/gendefs.h"
```

- This makes it possible to call the two commonly used graphics commands:

```
SAVE_DISPLAY_PREFS;
```

and

```
RESTORE_DISPLAY_PREFS;
```

- Following the convention already established, the captions will drawn using the command sequence:

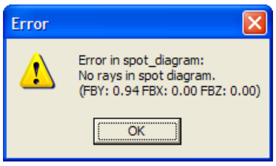
```
if (char_pref(glab)) draw_title_block(str1,str2,str3);
```

where the code for `draw_title_block(str1,str2,str3);` can be found in the CCL file **public/CCL/graph_tools.ccl**

Error handling

- Open the surface data spreadsheet and change the field angle to `30` degrees.

- Call the **xmt** procedure. The command will fail when the transmission falls to zero with an error message as shown.



The remedy is to add an error handling procedure to reset the error flag to zero. This will be called from xmt whenever an error occurs. If a procedure invokes a second procedure, then either the second must precede the first, or it needs to be declared:

- Add the line at the top, the prototype declaration (note that this one is followed by a semicolon):
  cmd xmt_error_handler();
- Declare an integer global variable **xmt_err** to carry the error status between the prcedures.
- Add the error handler command xmt_error_handler at the end.
- The error handler can now be called. Before the window command, add the line: **install_error_handler("xmt_error_handler");** and at the end add the command to restore the original (default) error handler:
  install_error_handler("prefs");

By adding the error handling precautions to the plotting routine, it is possible to prevent the execution of the spot diagram command if the chief ray has not been traced successfully and to continue execution of the command with the transmission value set to zero if no rays have been transmitted in the spot diagram. .

Listing of complete command xmt

- Convert the predefined variables to locally defined variables, **i** becomes **iplt, x** becomes **xplt**, **y** becomes **yplt**, and **k** becomes **ssb_row_sav**.
- Add comments, documentation, ticks and captions etc as shown below.
- Save and compile. The whole procedure now looks like this:

```
//
// Written by [your name] [date]
//

#include "../../public/ccl/inc/gendefs.h"

int xmt_err;//global variable

cmd xmt(void);
cmd xmt_error_handler(void);

cmd xmt(void)
// hlp:  <P>XMT</P>
// hlp:  <P>Plots the fall in transmission as a function of field
// hlp:  arising from central obstructions and vignetting. It does not
// hlp:  include the effects of coatings or Fresnel reflections.</P>
// hlp:  <P>This CCL command also illustrates how a custom error
// hlp:  handler prevents reference ray failures terminating execution
// hlp:  of a CCL command; by setting errno=0 within the error handler
// hlp:  it permits continued execution of the CCL command even after
// hlp:  what would otherwise be a fatal error. </P>
```

```
    {
    static int ssb_row_sav,iplt;
    static real xplt,yplt;
    static char str1[80],str2[80],str3[80];

    SAVE_DISPLAY_PREFS;//as defined in gendefs.h
    set_preference(output_text, off);//switches off text output
    ssb_row_sav = sbrow;//saves row after last row written to in SSB
    ssbuf_reset(ssb_row_sav, 1);//initialises spreadsheet buffer
    graphwin_reset;//clears graphics window

        install_error_handler("xmt_error_handler");// see below
        window(-0.2, 1.2, -35, 110);//xmin xmax ymin ymax
        moveto(0, 0);// draw x-axis (range 0...1)
        lineto(1, 0);
        for (iplt = 1; iplt <11; iplt++)
            {moveto(iplt*0.1, 0);//draw x-axis ticks
            linerel(0, -2);}
        moverel(-0.2,-10);
        label("Rel.Obj.Ht.");//label x-axis
        moveto(0, 0);// draw y-axis (range 0...100)
        lineto(0, 100);
        for (iplt = 1; iplt <11; iplt++)
            {
            moveto(0,iplt*10);//draw y-axis ticks
            linerel(-0.02,0.0);
            }
        moverel(-0.1,0);
        label("%s","100%");//label y-axis
        moveto(0,100);// plot transmission curve
        pen(2);//green
        for (iplt = 0; iplt <51; iplt++)
             {
             xplt=iplt*0.02;// xplt=Relative object height (FBY)
             yplt=0;
             xmt_err=0;
             set_object_point(xplt,0.0,0.0);
             if (xmt_err==0)// i.e. If sop succeeded ...
                 {
                 spot_diagram(44);
                 if(xmt_err==0)// .. and spd succeeded ...
                 yplt=ssb(6+8*iplt,1);//..set yplt ...
                 }// ... else yplt remains zero.
            lineto(xplt,yplt);
            }
        message("");// clears message area

        install_error_handler("prefs");// default - see asyst_ccl.ccl

    ssbuf_reset(-ssb_row_sav, 0);//restores ss buffer row numbering
    set_preference(output_text, on);//switches text output back on

    pen(1);// black
    if (char_pref(glab))// only if preference graphics_labels ON ...
        {
        sprintf(str1,"Field angle %.4f",180*ang/pi);
        sprintf(str2,"Object height %.6g",obh);
        sprintf(str3,"TRANSMITTANCE VS FIELD");
        draw_title_block(str1,str2,str3);//see public/graph_tools.ccl
        }
    gshow;//clears graphics buffer, forces display of graphics
    RESTORE_DISPLAY_PREFS;
    }

/******** ********* ********* ********* ********* ********* **********/

cmd xmt_error_handler(void)
    {
    xmt_err=errno;
    errno = 0;//clears error to permit CCL execution to continue
    }
```

The graphics window toolbar

Commands which generate graphical output are generally called from icons on one of the graphics window toolbars. The format for a graphics window toolbar is:

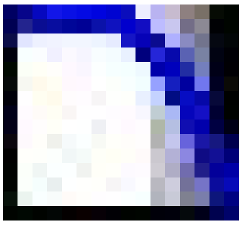
```
menu toolbar_number
        {
        "bitmap_file, tooltip_label"   = "gwt \"window_title\"; gwe \"command\";",
        ...
        }
```

where **bitmap_file.bmp** is the name of a bitmap file containing the icon, and stored in the folder **/Prm64/bin/bma**. Once again, **tooltip_label** appears in a cream-colored box when the cursor hovers over the icon. The **window_title** (up to 48 characters) will appear in the blue title bar of the updatable graphics window.

Creating a new icon for xmt

- Using the computer file listing facility, locate the redundant blank icon **blank1.bmp**, which is the first file in the directory **/[Prm64]/bin/bma** This is a file 16 x 15 pixels (all gray) with a palette of 16 colors, plotted at a resolution of 96 pixels per inch.
- Copy it to the same directory, and rename it **an_xmt.bmp**
- If time permits, modify the image pixel by pixel as shown, using a program such as Microsoft Paint®, and store it with the same name.

blank1.bmp



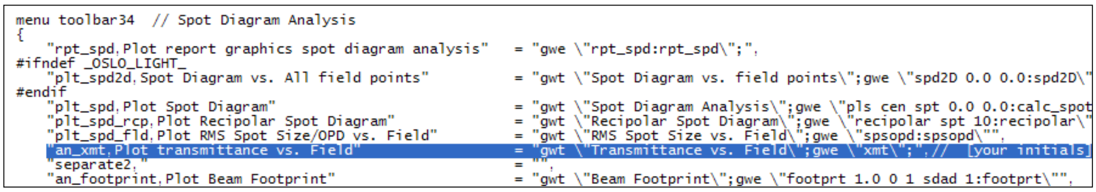
an_xmt.bmp

Adding the xmt icon to the graphics window toolbar

In **a_menu.ccl**, the toolbar number is 34 for the Spot Diagram Analysis graphics window.

- Open the Text Editor window, select **File > Open** and look in the Private CCL directory. Open the file **a_menu.ccl**.
- Locate toolbar 34. Go to line 1241 of this file (**Ctrl-G** and enter **1241** in the dialog box). On this line (or one nearby) should be the entries for the toolbar menu:

```
menu toolbar34  // Spot Diagram Analysis
```



```
menu toolbar34  // Spot Diagram Analysis
{
    "rpt_spd,Plot report graphics spot diagram analysis"   = "gwe \"rpt_spd:rpt_spd\";",
#ifndef _OSLO_LIGHT_
    "plt_spd2d,Spot Diagram vs. All field points"          = "gwt \"Spot Diagram vs. field points\";gwe \"spd2D 0.0 0.0:spd2D\"
#endif
    "plt_spd,Plot Spot Diagram"                            = "gwt \"Spot Diagram Analysis\";gwe \"pls cen spt 0.0 0.0:calc_spot
    "plt_spd_rcp,Plot Recipolar Spot Diagram"              = "gwt \"Recipolar Spot Diagram\";gwe \"recipolar spt 10:recipolar\"
    "plt_spd_fld,Plot RMS Spot Size/OPD vs. Field"         = "gwt \"RMS Spot Size vs. Field\";gwe \"spsopd:spsopd\"",
    "an_xmt,Plot transmittance vs. Field"                  = "gwt \"Transmittance vs. Field\";gwe \"xmt\";",//  [your initials]
    "separate2,"                                           = "",
    "an_footprint,Plot Beam Footprint"                     = "gwt \"Beam Footprint\";gwe \"footprt 1.0 0 1 sdad 1:footprt\"",
```

After the line:

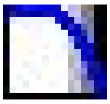
```
"plt_spd_fld,Plot RMS Spot Size/OPD vs. Field"  = "gwt \"RMS Spot Size vs.
Field\";gwe \"spsopd:spsopd\"",
```

add the following, all on one line (note the comma before the comment):

```
"an_xmt,Plot transmittance vs. Field" = "gwt \"Transmittance
vs. Field\";gwe \"xmt\";", // [your name] [date]
```

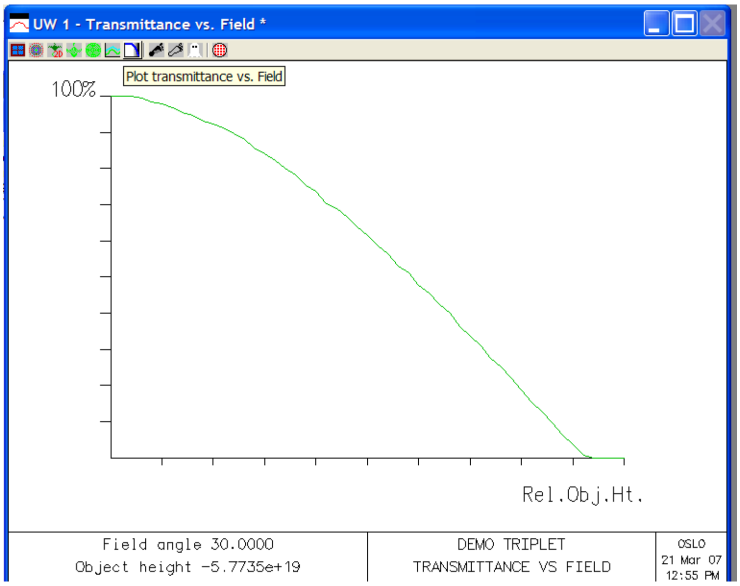
- Save **a_menu.ccl**.
- Check that compilation is successful:

```
*CCL COMPILATION MESSAGES:
No errors detected
```



Calling xmt from the toolbar icon

- Ensure that the lens in store is the standard triplet with 30 degrees as the semi-field angle.
- Open a new graphics window.
- Click on the Setup Window/Toolbar icon, and select the Spot Diagram menu.
- Click on the xmt icon shown above.



SCP programming: *triplet

SCP ("star command program") is the old macro language of OSLO, still supported but largely replaced by CCL. An SCP command consists of a text file whose name is the same as the command name, and whose first line is `*[cmd_name]` without a semicolon. All the other lines are commands ending with semicolons, and the file named **cmd_name.scp** must be stored in the directory **/private/scp.** The command is not compiled, so errors are not detected until the commands are executed.

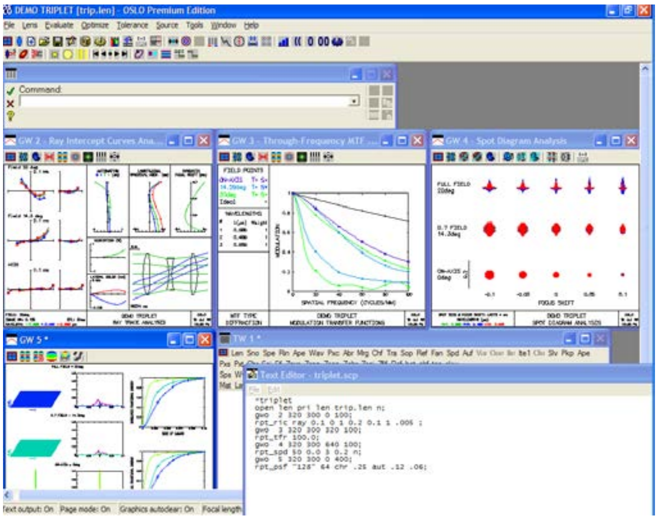
To call an SCP command, type `*[cmd_name]` into the command line.

- Open the text editor window.
- Click on **File > New**
- Type the following lines:

```
*triplet
open len pri len trip.len n;
gwo  2 320 300 0 100;
rpt_ric ray 0.1 0 1 0.2 0.1 1 .005;
gwo  3 320 300 320 100;
rpt_tfr 100.0;
gwo  4 320 300 640 100;
rpt_spd 50 0.0 3 0.2 n;
gwo  5 320 300 0 400;
rpt_psf "128" 64 chr .25 aut .12 .06;
```

The first line must begin with a * and have no semicolon after it. The first **gwo** command opens a new graphics window, GW2, which is 320 units wide and 300 high in the top left corner of the window, just under the command window. Three more windows are defined in the same way.

- Except for the very first line, the entries may be tested during entry by highlighting them with the cursor and pressing **Ctrl-E**.
- In the text editor window, click on **File > Save as ...**
- Change File type to **SCP**.
- Click on **PRIVATE** to store the command in **/private/scp/**
- Enter file name as **triplet.scp**. The file name must be the same as the command name, and only one command is permitted per file. Note that no compilation takes place, so there is no checking for errors before execution.
- This command opens the triplet stored in the private lens directory on installation, and plots the ray intersection coordinates, the MTF, the spot diagram and the point spread function at three field point. Parameters for each of these commands are chosen to suit the lens.



- To call this SCP command, type:

  ***triplet**

  including the initial asterisk.

Some examples of SCP commands are given in the directory **/public/scp.**

Load command file programming

This is available only in OSLO Standard and Premium versions.

The command **lcmd** opens a text file and executes the OSLO commands in sequence. Unlike CCL and SCP files, the location of the file is quite arbitrary, so this programming language has the advantage that the files can be stored with the lenses. Semicolons at the end of each line are optional, but including them makes it easier to check the command file while it is being developed, using **Ctrl-E** in the text editor window.

- Open the text editor and type:

```
//triplet [your name] [date]
open len pri len trip.len n;
gwo  2 320 300 0 100;
rpt_ric ray 0.1 0 1 0.2 0.1 1 .005;
gwo  3 320 300 320 100;
rpt_tfr 100.0;
gwo  4 320 300 640 100;
rpt_spd 50 0.0 3 0.2 n;
gwo  5 320 300 0 400;
rpt_psf "128" 64 chr .25 aut .12 .06;
```

- In the text editor window, click on **File > Save as ...**
- Store it as a text file in the **private/len** directory with type **.txt** and with the name **triplet.cmd**.
- To execute, type in the command line **lcmd,** search in the **private/len** directory for the command file **triplet.cmd**, and click on **Open** to execute.

Chapter 9 - Optimization

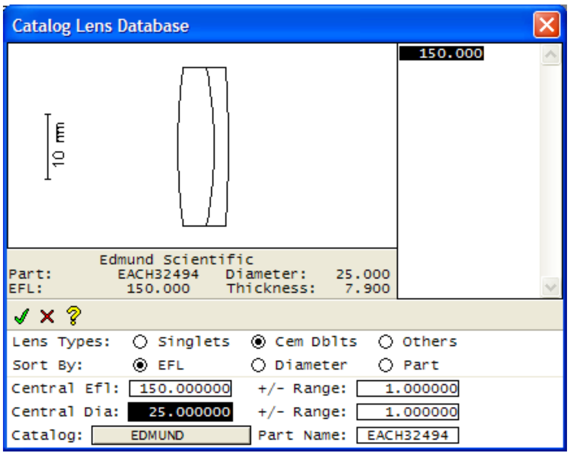
Optimizing using Seidel aberrations

According to Seidel aberration theory, a thin cemented doublet of a specified pair of glass types (one crown, one flint) may in general be corrected exactly for only two of the three coefficients for primary axial chromatic aberration (PAC), spherical aberration (SA3), and coma (CMA3). Using one real and one fictitious glass, however, an exact solution can always be found.

This exercise will show how to find, using Seidel aberrations alone, the nearest glass in the Schott catalog to combine with Schott N-BAK4 making a cemented doublet of a focal length 150 mm, and aperture ratio f/6.3.

Setting up the starting design

- Open a new lens surface spreadsheet.
- Select the image surface. Click on the gray **SRF** button, right click, and choose **Insert catalog lens.**
- Select the **EDMUND** catalog, and look for a ◉ **cemented doublet** focal length **150** mm diameter **25** mm.
- If +/-1 mm ranges are chosen there is only one result. The Edmund catalog number for this lens is **EACH32494**. The glass types used in this lens are Schott BK7 for the crown and Schott SF5 for the flint.
- Set the entrance beam radius to be **150/2/6.3** mm.



- Set the semi field angle to **1**°.
- Set wavelength weights **1.0** (0.58756µm) **0.4** (0.48613 µm), **0.6** (0.65627 µm).
- Delete the extra surface, by clicking on the gray **SRF** button for surface AST, right click, and choose **Delete.**
- We need to be able to alter surfaces 1 2 and 3. Click on the gray **SRF** button for surface 1 (AST), right click, and choose **Ungroup.**
- Set the image distance at the paraxial back focal point (under thickness for surface 3, select **Solves (S) > Axial ray height > Solve value = 0.0**).
- Listing the lens at this stage gives:

```
*LENS DATA
Doublet f/6.3 150 mm
 SRF       RADIUS       THICKNESS   APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ        --         1.0000e+20    1.7455e+18             AIR

 AST     91.370000      5.700000     12.500000 A            BK7 C
  2     -66.210000      2.200000     12.500000              SF5 C
  3    -197.710000    146.149598 S   12.500000              AIR

 IMS        --             --         2.618244 S
```

Defining the error function

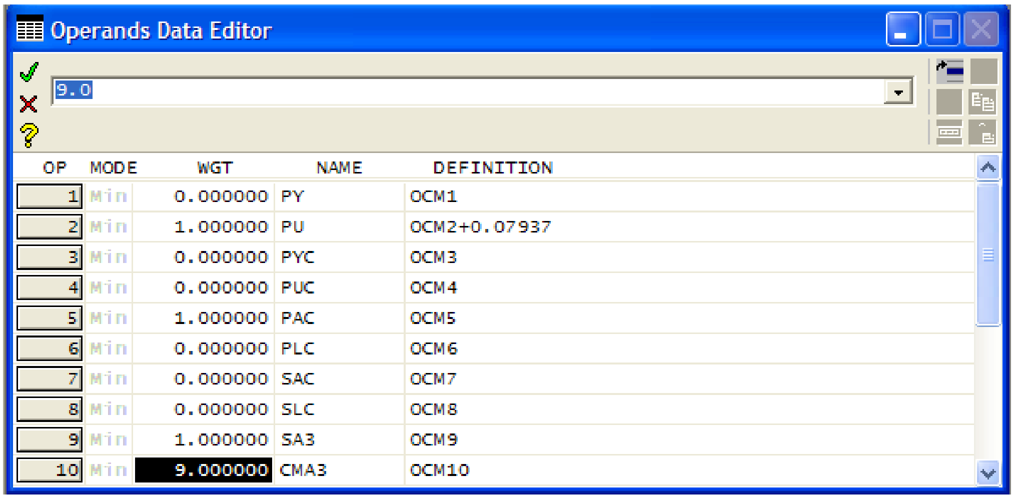
- First, close all open spreadsheets (this is important).
- Calculate the angle for the marginal axial ray angle at the image for an f/6.3 beam: Type into the command window `0.5/6.3` and record the result:

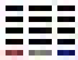
Result = 0.0793650793651

- From the **Optimize** menu header, select **Generate error function> Aberration operands**
- Then, in the operands data editor which opens, set non-zero weights for just the four operands listed below:

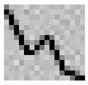
OPERAND	MODE	WEIGHT	NAME	DEFINITION
2	MIN	1.0	PU	OCM2+0.07937
5	MIN	1.0	PAC	OCM5
9	MIN	1.0	SA3	OCM9
10	MIN	9.0	CMA3	OCM10

For each operand, the **MODE** is MIN (minimization) rather than CON (constraint) which is equivalent to an infinite weight. (The latter is rarely of value). The **WEIGHT** gives the relative importance of each operand, and here coma has (arbitrarily) been given higher weight than the other two aberrations. The **NAME** is for information only, and has no effect on the optimization process. The **DEFINITION** is a string `OCM` followed by the element number of the optimization common matrix, Ocm[], that contains the value of the relevant operand calculated by the optimization CCL callback procedure **opcb_abs**. This string may include one arithmetical operand and one constant.
For example, operand 2, sets the non-zero target value for PU (the axial ray angle in image space) to be equal to -0.07937. The entrance beam radius is fixed, so that, by controlling the value of PU in the image space, the focal length of the lens will be controlled to be at or near 150 mm since the optimization will seek to reduce the operand PU-0.07937 to zero. Of course defining operand 21 (EFL) as OCM21-150.0, and assigning it a non-zero weight, would have had the same effect.





- Close the operands data editor spreadsheet. If it needs to be opened again press the **Edit optimization operands** icon.



- Click on the icon to open the optimization conditions spreadsheet.
- Note the entry for the optimization callback, **Command for CCL/SCP operands:** **`opcb_abs`**
- On the bottom line, under **Error function value**, select ⦿ **Weighted sum of squares**.

Hence the formula for this error function becomes:

*Min error fn = 1 * (PU + 0.07973)*^{2} *+ 1 * (PAC)*^{2} *+ 1 * (SA3)*^{2} *+ 9 * (CMA3)*^{2}

- Close the optimization conditions spreadsheet.

To list the starting value of the error function and its component operands:

- In the text window, click on **Ope**

```
*OPERANDS
 OP   MODE    WGT       NAME          VALUE   %CNTRB DEFINITION
O 2    M     1.000000 PU          4.4317e-06    0.00 OCM2+0.07937
O 5    M     1.000000 PAC          -0.003508   34.19 OCM5
O 9    M     1.000000 SA3          -0.004828   64.76 OCM9
O 10   M     9.000000 CMA3          0.000205    1.05 OCM10
...
MIN ERROR FUNCTION:   3.5988e-05
```

- To print the minimization error function alone, type the command:

```
ope erf
```

```
MIN ERROR FUNCTION:   3.5988e-05
```

Description of the Aberration Operands error function

The aberration operands error function consists of a set of predefined operands, including paraxial ray heights and angles, and Seidel and Buchdahl aberration coefficients. All the default weights are zero, so that at least one non-zero weight must be specified before it be used.

The menu header sequence which generates the error function calls the CCL command **opabs_template** in file **/public/CCL/optim_erfs.ccl.** This includes a command:

```
opt_oprdccl("opcb_abs");
```

which sets the CCL command **opcb_abs** (in file **/public/CCL/optim_callbaks.ccl**) as the optimization callback. This in turn contains CCL code which is called every time the error function is evaluated. This callback command, **opcb_abs**, outputs the values of Gaussian and Seidel quantities to the text window spreadsheet, and then copies selected values into the Ocm[] matrix. The key lines of the code from the command **opcb_abs** are listed here:

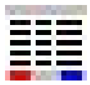
```
paraxial_trace();
Ocm[2] = ssb(1, 2); // pu
chromatic_abers();
Ocm[5] = ssb(2, 1); // pac
seidel_abers();
Ocm[9] = ssb(3, 1);  // sa3
Ocm[10] = ssb(3, 2); // cma3
```

The relevant lines of CCL in the **opabs_template** command, which sets up the operands, are:

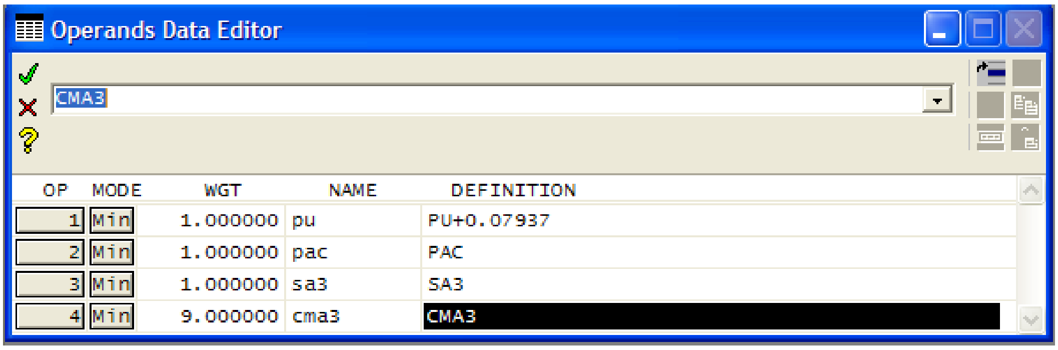
```
operands(new);
        opnbr = 0;
        opnbr++;o(opnbr, ins, "OCM1 ", 0.0, "PY");   /* Axial ray height */
        opnbr++;o(opnbr, ins, "OCM2 ", 0.0, "PU");   /* Axial ray slope */
        opnbr++;o(opnbr, ins, "OCM3 ", 0.0, "PYC");  /* Chief ray height */
        opnbr++;o(opnbr, ins, "OCM4 ", 0.0, "PUC");  /* Chief ray slope */
        opnbr++;o(opnbr, ins, "OCM5 ", 0.0, "PAC");  /* Primary axial color */
        opnbr++;o(opnbr, ins, "OCM6 ", 0.0, "PLC");  /* Primary lateral color */
        opnbr++;o(opnbr, ins, "OCM7 ", 0.0, "SAC");  /* Secondary axial color */
        opnbr++;o(opnbr, ins, "OCM8 ", 0.0, "SLC");  /* Secondary lateral color */
        opnbr++;o(opnbr, ins, "OCM9 ", 0.0, "SA3");  /* 3rd-order spherical */
        opnbr++;o(opnbr, ins, "OCM10", 0.0, "CMA3"); /* 3rd-order coma*/
        ...
        end();
```

Users of OSLO Standard and OSLO Premium do have the facility to define the error function as here described. However they do have a more direct way to define the error function, using predefined operands with self-explanatory names. This obviates the need for a CCL callback. The procedure for this is:

- Delete any pre-existing operands using the command sequence:
  `ope new;end`



- Open the operand spreadsheet.
- Add three blank lines and then fill in the entries as shown in the diagram:



- Close the operands data editor spreadsheet and click on **Ope** to list the operands.

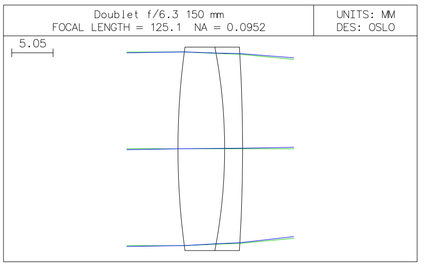
Creating a model glass

Before a glass type can be made variable, it needs to be converted to a "model" glass. Open the lens data spreadsheet. Change the glass at surface 1 from **BK7** to **N-BAK4**

- Under **GLASS** for the second surface, click on the gray button next to **SF5** and select **Model... (M).**
- Press **Enter** three times to accept the default name (**GLASS2**), refractive index, and Abbe V-value.
- Click on **Rin** to list the refractive indices. Although the model glass is specified only by its refractive index at the d wavelength and Abbe number, the refractive index data for F and C wavelengths remain almost unchanged.

Defining the optimization variables

- In the surface data spreadsheet, define the variables: Under **GLASS** for the second surface GLASS2, click on the gray button, and select **Variable RN/DN.** (The **Special Variable RN/DN** option is exactly equivalent). Note that although the Abbe number is used to define the dispersion for the model glass it is the OSLO "DN" which is used as a variable. This is a normalized parameter, best visualized in the index-dispersion plot. DN takes a value of 0.0 along the line joining N-FK5 and N-SK16, and a value of 1.0 along the line joining N-FK5 and SF11. Nearly all catalog glasses sit between these two lines, but most of the "normal" glasses tend to cluster about DN = 1.0.



- Click on the variables button at the top of the spreadsheet, and put an upper limit of **1.0** for the value of DN, the dispersion parameter for surface 2. Leave the lower limit as **0**.
- Also set the minimum value of RN surface 2 as **1.48**, the index of FK51, and the maximum value **1.85**, the index of N-LaSF9, the highest index glass which can be regarded as having reasonable cost and acceptable environmental properties.
- Click on "Vary all curvatures".
- Close the variables spreadsheet and the surface data spreadsheet.
- Save the lens. The listing is given here:

```
*LENS DATA
Doublet f/6.3 150 mm
 SRF       RADIUS       THICKNESS   APERTURE RADIUS      GLASS  SPE  NOTE
 OBJ        --         1.0000e+20    1.7455e+18            AIR

 AST     91.370000 V    5.700000     12.500000 A        N-BAK4 C
  2     -66.210000 V    2.200000     12.500000          GLASS2 V
  3    -197.710000 V  121.451048 S   12.500000             AIR

 IMS        --             --          2.182779 S
```

Optimization

- Using the header of the Text window, list the operands (**Ope**) and the variables (**Var**).

```
*OPERANDS
 OP   MODE     WGT       NAME           VALUE   %CNTRB DEFINITION
O 1    M       --       PY          1.7764e-15    --   OCM1
O 2    M    1.000000 PU              -0.015829   2.24 OCM2+0.07937
O 3    M       --       PYC          2.182779    --   OCM3
O 4    M       --       PUC          0.017260    --   OCM4
O 5    M    1.000000 PAC             -0.081694  59.77 OCM5
O 6    M       --       PLC          -0.000343    --   OCM6
O 7    M       --       SAC          -0.053498    --   OCM7
O 8    M       --       SLC          -0.000226    --   OCM8
O 9    M    1.000000 SA3             -0.063974  36.65 OCM9
O 10   M    9.000000 CMA3             0.004069   1.33 OCM10
....
MIN ERROR FUNCTION:     0.011166

*VARIABLES
 VB    SN  CF  TYP        MIN         MAX        DAMPING      INCR        VALUE
V 1     2   -  CV         --          --         1.000000   0.000100     0.010945
V 2     3   -  CV         --          --         1.000000   0.000100    -0.015103
V 3     4   -  CV         --          --         1.000000   0.000100    -0.005058
V 4     3   -  RN       1.480000    1.850000     1.000000   0.001000     1.672698
V 5     3   -  DN         --        1.000000     1.000000   0.001000     0.929017
```

- Optimize for 10 cycles (**Ite**).

```
*ITERATE FULL   10
NBR      DAMPING   MIN ERROR   CON ERROR  PERCENT CHG.
  0   1.0000e-08    0.011166      --
  1     3.792096    0.002771      --        75.179931
  2     0.002633  6.6051e-06      --        99.761674
  3     0.000615  2.4247e-07      --        96.329101
  4   7.8298e-06  1.0315e-12      --        99.999575
  5   1.2696e-09  2.4261e-19      --        99.999976
  6   1.2696e-09  1.0128e-25      --        99.999958
  7   1.2696e-09  1.0075e-31      --        99.999901
  8     1.269595  8.3919e-32      --        16.703389
```

Choosing a real glass type

- Find the DN value of the new glass:

var 5

```
*VARIABLES
 VB    SN  CF  TYP        MIN         MAX        DAMPING      INCR        VALUE
V 5     2   -  DN         --        1.000000     1.000000   0.001000     0.998766
```

- List its refractive indices and Abbe V-value

rin 2 2

```
*REFRACTIVE INDICES
 SRF   GLASS/CATALOG         RN1         RN2         RN3        VNBR        TCE
  2    GLASS2             1.694707    1.711261    1.687937   29.785506   82.000000
```

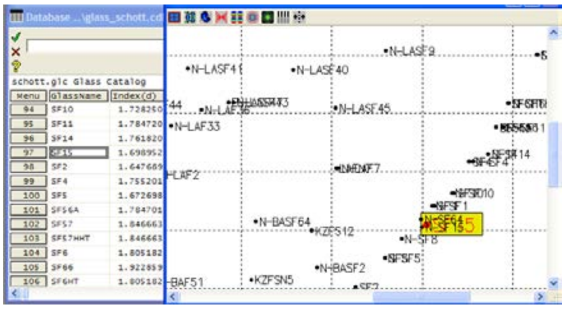
- Open the surface data spreadsheet.
- Click on the gray button for surface 2 glass.
- Select **FIX** and choose the latest Schott catalog (either **Schott**, or **Schott 2004**, depending on the edition of OSLO). In any event the glass chosen should be SF-15.
- Enter **rin 2 2:**

```
*REFRACTIVE INDICES
 SRF   GLASS/CATALOG         RN1         RN2         RN3        VNBR        TCE
  2    SF15               1.698952    1.715461    1.692215   30.067619   79.000000
       SCHOTT
```

- Open the glass catalog database.

- From the menu header select **File >Open database > PUBLIC > glass_schott.cdb** (it may be **glass_schott2004.cdb** in some versions of OSLO)

- In the GLASSNAME column, click on **SF15**.



Note that the glass is highlighted in yellow on the n-V diagram. The atmospheric and chemical properties are found in the column labeled **ChemCode** (**10112**). These are not bad, but a better glass, the lead- and cadmium-free equivalent is N-SF15 with a **ChemCode** of **10111**.

- Change the glass for surface 2 to **N-SF15**: under the gray button for GLASS, select **Catalog > Schott** and click on **N-SF15** - it is not possible to just type in the name to replace a model glass.

Final optimization steps

Reoptimize with the remaining parameters (the three surface curvatures).

- Click on **Ite**:

```
*ITERATE FULL  10
NBR      DAMPING   MIN ERROR   CON ERROR  PERCENT CHG.
  0  1.0000e-08  2.7751e-05      --
  1  1.0000e-12  2.7540e-05      --         0.759895
  2  1.0000e-12  2.7520e-05      --         0.073851
  3  1.0000e-12  2.7519e-05      --         0.003876
  4   10.000000  2.7519e-05      --       1.0937e-06
```

Autofocus

Refocus to minimize the root mean square axial wave aberration, averaged over the three wavelengths:

- Open the surface data spreadsheet.

- Under the gray THICKNESS button for surface 4 select **Autofocus - minimum RMS OPD > On axis (polychromatic).**

- Right click on the text window, and choose **Clear window and SS buffer.**

- Click on **Len**

```
*LENS DATA
Doublet f/6.3 150 mm
 SRF       RADIUS       THICKNESS    APERTURE RADIUS        GLASS   SPE   NOTE
 OBJ         --         1.0000e+20    1.7455e+18              AIR

 AST     94.166056 V     5.700000     12.500000 A        N-BAK4 C
  2     -67.121889 V     2.200000     12.500000          N-SF15 C
  3    -273.328281 V   146.658952 S   12.500000             AIR

 IMS         --          0.080939      2.639626 S
```

- It is worth combining the distances for surfaces 3 and 4 to avoid confusion: Click on the defocus value.

b5 = 0.0809387292198

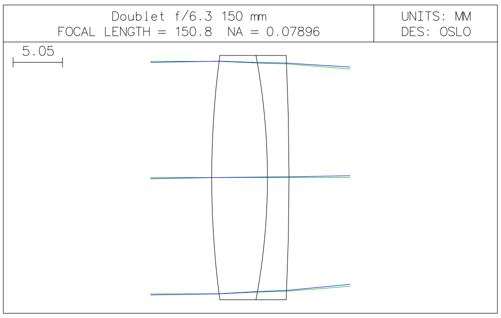
- In the surface data spreadsheet, set the defocus value (thickness surface 4) to `0`.
- Also click on the thickness for surface 3, and in the command line add `+b5`.

`146.6589521609103+b5`

- Finally, list the lens again:

```
*LENS DATA
Doublet f/6.3 150 mm
 SRF       RADIUS       THICKNESS    APERTURE RADIUS        GLASS   SPE   NOTE
 OBJ         --         1.0000e+20    1.7455e+18              AIR
 AST     94.166056 V     5.700000     12.500000 A        N-BAK4 C
  2     -67.121889 V     2.200000     12.500000          N-SF15 C
  3    -273.328281 V   146.739891     12.500000             AIR
 IMS         --             --         2.639626 S
```

.



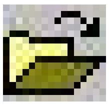
Optimization using finite rays

The optimization exercise described in this section will be carried on into the tolerance calculations of the next chapter. Because the starting design is well optimized, the initial choice of error function and weights is not critical. The GENII error function, which is given in all versions of OSLO, will be used for the initial design stages.

50 mm f/5.6 objective: specification

Design a triplet objective with a focal length of 50 mm, and a 15º semi-field of view, with aperture f/5.6. Vignetting is not permitted - that is to say, the full diameter beam must pass at all field angles. The final detector will be a photographic film with resolution out to 30 cycles/mm, and an MTF of at least 0.1 is required at this spatial frequency. Distortion is not critical. Only current Schott glass types can be used, and manufacture is to be at Rodenstock, by traditional methods, with dimensions marked on the final drawing in mm.

Finding a starting design



The most obvious starting point is the standard triplet supplied with the program. The first task is to set it up with the correct field, aperture and wavelength weights and to allow the aperture stop (drawn with a red pen) to move separately, rather than being assigned to an air-glass surface:

- Click on the icon for **Open an existing lens**.
- At the bottom of the window which opens, after **Library Directories:** click on **Public**.
- Select **demo > edu** and then click on **demotrip.len**.

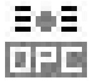
- Click on **Open**.
- Open the surface data spreadsheet.
- Change the lens identifier to **50 mm f/5.6 +/-15deg**
- Click on **Wavelength**. Define the wavelength weights as **1.0** (.58756) **0.4** (.48613), **0.6** (.65627) and close the wavelength editor.
- Click on **Notes**, delete all 5 lines of notes and replace with your own annotations.
- Change the entrance beam radius to **4.5** mm. That is, 50/5.6/2, rounded up.
- Change the field angle to **15**°
- Click on the gray button for **Aperture radius** for surface 1, select **Not checked**. Repeat for surface 6.
- Click on surface 5.
- Right click and select **Insert before**
- Change thickness for surface 4 from 6 to **0.0,** and thickness for surface 5 frm 0 to **6.0.**
- Click on the button for **Aperture radius** for surface 5, and select **Aperture stop**.
- Click on the gray button under **Special** for surface **5 (AST).**
- Select **Surface Control (F) > General**

- On the second line, against **Surface appearance in lens drawings:** select **Drawn.** Set the **Pen number for surface in lens drawings** as **4** (red).

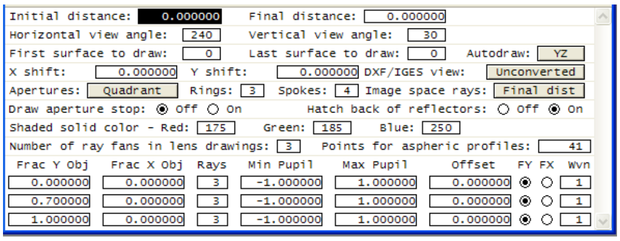
- Set all the lens aperture radii to **Solve**. The aperture pickup on surface 2 vanishes.

Checking for vignetting in the starting design

In the triplet provided, the ray drawing conditions have been changed to allow for the vignetting. The first need is to restore the off-axis beams drawn to their full diameter.



- Click on the Edit Lens Drawing Conditions icon.

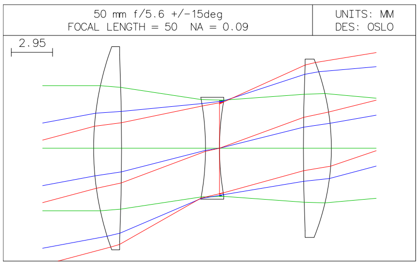


- In the section which governs rays drawn at the foot of the spreadsheet, change the number of rays for fan No. 2 from **0** to **3**. Set the Min Pupil to **-1.0** and the Max Pupil to **+1.0** for fan No. 3.

- Close the Lens Drawing Conditions spreadsheet.

- Draw the lens.

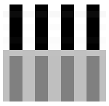
- Click on **Len Wav** and **Pxc** to list the lens.



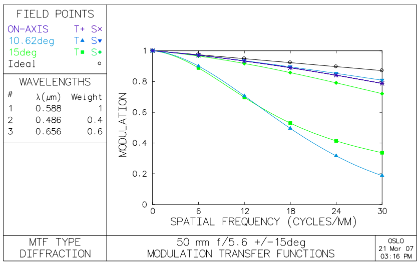

```
*LENS DATA
50 mm f/5.6 +/-15deg
 SRF      RADIUS        THICKNESS   APERTURE RADIUS      GLASS  SPE  NOTE
 OBJ        --         1.0000e+20    2.6795e+19           AIR

  1     21.250000       2.000000       7.304439 S         SK16 C
  2   -158.650000       6.000000       6.710505 S          AIR

  3    -20.250000       1.000000       3.665807 S           F4 C
  4     19.300000          --          3.420953 S          AIR

 AST        --          6.000000       3.420953 AS         AIR      *

  6    141.250000       2.000000       5.931324 S         SK16 C
  7    -17.285000      42.950000       6.415576 S          AIR

 IMS        --             --         13.376446 S

*WAVELENGTHS
CURRENT  WV1/WW1      WV2/WW2      WV3/WW3
   1     0.587560     0.486130     0.656270
         1.000000     0.400000     0.600000

*PARAXIAL CONSTANTS
   Effective focal length:    50.000541    Lateral magnification:  -5.0001e-19
   Numerical aperture:         0.089999    Gaussian image height:    13.397605
   Working F-number:           5.555616    Petzval radius:         -149.381547
   Lagrange invariant:        -1.205771
```

Assessing the starting design

The diagram above indicates the edge thicknesses of the positive components are far too small for economic manufacture. The center thickness of the negative lens needs increasing as well. And the stop needs to move away from the second surface of the negative lens to allow a plane diaphragm plate to be used.

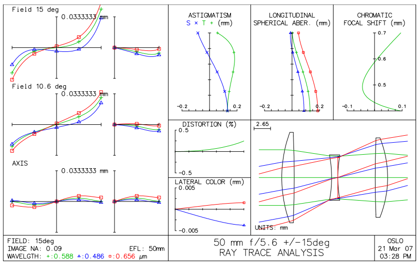


- In the Standard Tools graphics menu, click on the Through-Frequency MTF icon.



- Right click in the graphics window, and select **Recalculate with new parameters...**
- Enter **Maximum frequency** `30` cycles/mm.

The resolution, especially in the off-axis points, needs improvement, but otherwise the performance is good.

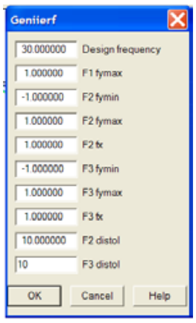


  - Click on the icon for ray intercept curves.
  - Right click in the graphics window, and select **Recalculate with new parameters...**
  - Enter a value of `0.03333` mm (the reciprocal of the customer-defined spatial frequency) for the **User aberration scale.**

The transverse aberrations at all wavelengths in the meridional (Y) section off axis particularly need to be reduced.

Defining and validating the error function

- From the **Optimize** menu header, select **Generate error function > GENII Ray Aberration...**
- Fill in the entries for a **Design frequency** of `30` cycles/mm.

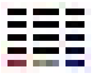


- Fill in the pupil coordinates on the basis of no vignetting: **F1** (on axis) **fymax** = `1.0` **F2** (0.7 field) **fymin** = `-1.0` **fymax** = `1.0` **fx** = `1.0` **F3** (edge of field) **fymin** = `-1.0` **fymax** = `1.0` **fx** = `1.0`.
- The tolerance on distortion at both F2 and F3 is **distol** = `10`% (in other words, distortion will not be tightly controlled).
- Finally click on **OK** to close the Geniierf spreadsheet.
- Type in the command line `ope all` to list the operands that have been defined by this command. (Operands which begin with an underscore are not listed by clicking on the **Ope** icon in the text window.)

Only the first 13 are listed below.

```
*OPERANDS
 OP  MODE    WGT      NAME          VALUE  %CNTRB DEFINITION
O 1   M      --     _Dy tol       0.005556    --  0.0055555555556
O 2   M      --     _2.1 Dy       0.011667    --  0.0116666666667
O 3   M      --     _2.8 Dy       0.015556    --  0.0155555555556
O 4   M      --     _3 Dy         0.016667    --  0.0166666666667
O 5   M      --     _4 Dy         0.022222    --  0.0222222222222
O 6   M      --     _up Dy/3      0.283656    --  0.283655904077
O 7   M      --     _3.2 up Dy    2.723097    --  2.72309667914
O 8   M      --     _uprime    -3.5749e-14    --  PU+0.0899990260196
O 9   M    1.000000 Fnb diff   -3.5749e-10   0.00 O8/0.0001
O 10  M    1.000000 Focus diff    0.704983   0.26 DYY(1,1)/O4
O 11  M    1.000000 Axial DY      0.035247   0.00 DY(1,2)/O1
O 12  M    1.000000 Axial OPD    -1.189682   0.75 OPD(1,2)/O6
O 13  M    1.000000 Axial DMD     1.828939   1.78 DMD(1,2)/O6
```

The first weighted operand controls the focal length rather tightly. In the initial stages of design it is preferable that this be relaxed. So:



- Click on the icon for Edit optimization operands.
- Change the weight for operand 9 from 1.0 to **0.1**.
- List the operands, noting in particular any that have contributions above 10%. They are:

```
O 21  M    1.000000 0.7 OPD U    -5.224602  15.30 OCM21/OCM6
O 22  M    1.000000 0.7 DMD U     4.600139  11.86 OCM22/OCM6
O 24  M    1.000000 0.7 OPD L    -4.782094  12.82 OCM24/OCM6
O 36  M    1.000000 1.0 OPD U    -5.267896  15.55 OCM36/OCM6
O 37  M    1.000000 1.0 DMD U     6.020660  20.31 OCM37/OCM6
```

These are respectively, for the 0.7 field point, wave aberration and color for the upper Y-section ray, and wave aberration for the lower ray; also for the full field, wave aberration and color for the upper Y-section ray. These are the same aberrations as the plot above indicates will be causing the greatest reduction in MTF, so the error function has been validated.

Note that the initial value for the error function is given on the last line of the operand listing as the root mean square of the weighted contributions:

```
MIN RMS ERROR:     2.434848
```

Description of the GENII error function

The GENII error function provided with all versions of the program is remarkably sparse yet effective. It makes maximum use of the results of ray-tracing from a single marginal ray on axis, and a chief ray and three rays in the pupil for each of two other field angles. The aberrations of these rays constitute the error function.

The error function has two weighted operands controlling the Gaussian properties, three to control the axial image formation (transverse ray aberration DY, wave aberration OPD and Conrady chromatic variation in wave aberration DMD for color control), and 13 to control the four rays at each of the off-axis points at FBY = 0.7 and 1.0. This makes a total of 31, leaving the remaining 19 for necessary data storage.

Because the dimensions of transverse ray aberrations, wavefront aberrations, longitudinal errors and color are so different, the error function uses scaling factors on each to enable the default value of unity weighting as the starting value for each operand. For example, the basic scaling factor on transverse errors is $(6\ N)^{-1}$ where N is the design spatial frequency.

Defining the error function invokes a call to **geniierf()** (or, for users of OSLO EDU, **geniierf_lt**) which is in **public/ccl/optim_erfs.ccl**. The OSLO EDU version specifies **geniiops** as a callback, which will be found in **public/ccl/optim_callbaks.ccl.** More information is available in OSLO Help.

Defining the optimization variables

- Open the surface data spreadsheet.
- Click on the gray button for thickness 2, and select **Variable**.
- Repeat for thicknesses 4, 5, 7.
- Click on the **Variables** button to open the variables spreadsheet.
- Click on the **Vary all curvatures** button.
- For variable 2 (thickness 4) set a MIN value of **0.5** mm, leaving all other limits as default.
- Close the variables spreadsheet.
- Close the surface data spreadsheet
- List the optimization variables by clicking on **Var:**

*VARIABLES

VB	SN	CF	TYP	MIN	MAX	DAMPING	INCR	VALUE
V 1	2	-	TH	0.100000	1.0000e+04	1.000000	0.000450	6.000000
V 2	4	-	TH	0.500000	1.0000e+04	1.000000	0.000450	-- *
V 3	5	-	TH	0.100000	1.0000e+04	1.000000	0.000450	6.000000
V 4	7	-	TH	0.100000	1.0000e+04	1.000000	0.000450	42.950000
V 5	1	-	CV	--	--	1.000000	2.2222e-05	0.047059
V 6	2	-	CV	--	--	1.000000	2.2222e-05	-0.006303
V 7	3	-	CV	--	--	1.000000	2.2222e-05	-0.049383
V 8	4	-	CV	--	--	1.000000	2.2222e-05	0.051813
V 9	6	-	CV	--	--	1.000000	2.2222e-05	0.007080
V 10	7	-	CV	--	--	1.000000	2.2222e-05	-0.057854

There is an asterisk against thickness 4 indicating that the current value of the variable (=0) violates the permitted range. As a result, the error function has increased.

- Click on the **Ope** in the text window.

MIN RMS ERROR: 3.772815

Optimization

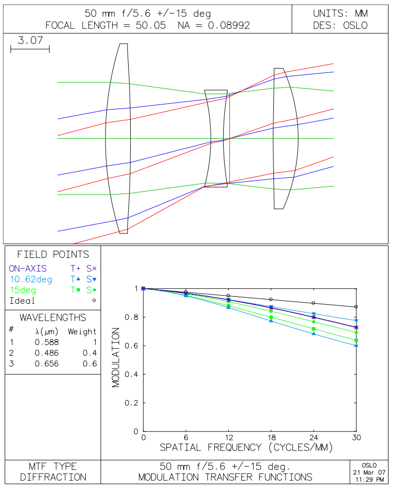
- Two clicks on the **Ite** button gives the output shown below for this error function.

*ITERATE FULL 10

NBR CHG.	DAMPING	MIN ERROR	CON ERROR	PERCENT
0	1.0000e-08	3.772815	--	
1	1.0000e-05	2.061430	--	45.360945
2	1.0000e-05	1.548952	--	24.860311
3	1.0000e-05	1.326489	--	14.362182
4	6.1580e-06	1.295507	--	2.335646
5	2.3352e-06	1.292165	--	0.257970
6	2.3352e-06	1.292093	--	0.005549
7	0.000144	1.292093	--	2.4329e-05

*ITERATE FULL 10

NBR CHG.	DAMPING	MIN ERROR	CON ERROR	PERCENT
0	1.0000e-08	1.292093	--	
1	1.0000e-08	1.292093	--	--
2	1.0000e-08	1.292093	--	--



If warning messages about clear aperture checking appear with OSLO EDU they will not affect the result significantly, although the final error function may differ slightly from the values given here..

The performance has improved considerably - the lowest MTF at 30 cycles/mm is 0.6 (for T section at .7 field). The prescription is:

```
*LENS DATA
50 mm f/5.6 +/-15 deg
 SRF       RADIUS       THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ        --         1.0000e+20    2.6795e+19             AIR

  1     25.838240 V    2.000000      7.591942 S            SK16 C
  2   -103.139037 V    6.389728 V    7.036229 S             AIR

  3    -14.888983 V    1.000000      3.888863 S              F4 C
  4     22.497814 V    0.499055 V    3.683790 S             AIR

 AST        --         3.457640 V    3.568729 AS            AIR   *

  6    161.514578 V    2.000000      5.108018 S            SK16 C
  7    -13.810731 V   44.869598 V    5.633273 S             AIR

 IMS        --            --        13.373470 S
```

The focal length is 50.05 mm, an error of less than 0.1% so there is no need to increase the weight on operand 9.

Engineering aspects: edge thicknesses

As this lens is to be made by traditional means, a blank needs to be procured with sufficient extra diameter to allow each component to be centered by edging. The thicknesses of all the lenses need to be increased to improve manufacturing yield. Making an allowance of 3 mm on diameter beyond the largest clear aperture diameter for the mounting (with an extra 1 mm on the front lens to allow for weather-proofing), and a further 2 mm for the blank, the edge thickness of each blank should be about 1.5 mm minimum.

To calculate the edge thicknesses of the blanks for the two positive lenses:

- From the **Lens** menu header select **Show Auxiliary Data > Edge Thickness**.
- For component 1, enter surface **A** =**1**, surface **B** = **2**. Enter the clear semi-diameter 7.6 mm plus 3 mm = **10.6** mm for the **y-height** at both surfaces:

```
*DISTANCE FROM SRFA  1 TO SRFB  2
 AT  YHTA         YHTB         XHTA         XHTB        ZSAGA       ZSAGB
   10.600000   10.600000      --           --        2.274242   -0.546529
 IS  XDIS         YDIS         ZDIS     GLOBAL DISTANCE
      --           --       -0.820771    0.820771
```

The edge thickness given (ZDIS) is -0.82 mm, so the centre thickness for surface 1 needs to be increased by about 2.8 mm to reach the target of 1.5 mm.

- Repeating for surface **A** =**6**, **B** = **7**, enter 5.6+2.5 = **8.1** mm for the **y-height** at both surfaces. otherwise type the command:

```
eth  6 7 8.1 8.1 0 0
```

For this lens, the edge thickness of the blank (ZDIS) is -0.83 mm, so the centre thickness for surface 6 also needs to be increased by about 2.8 mm.

The centre thickness of the negative lens (surface 3) is too thin, and should also be increased to 1.5 mm.

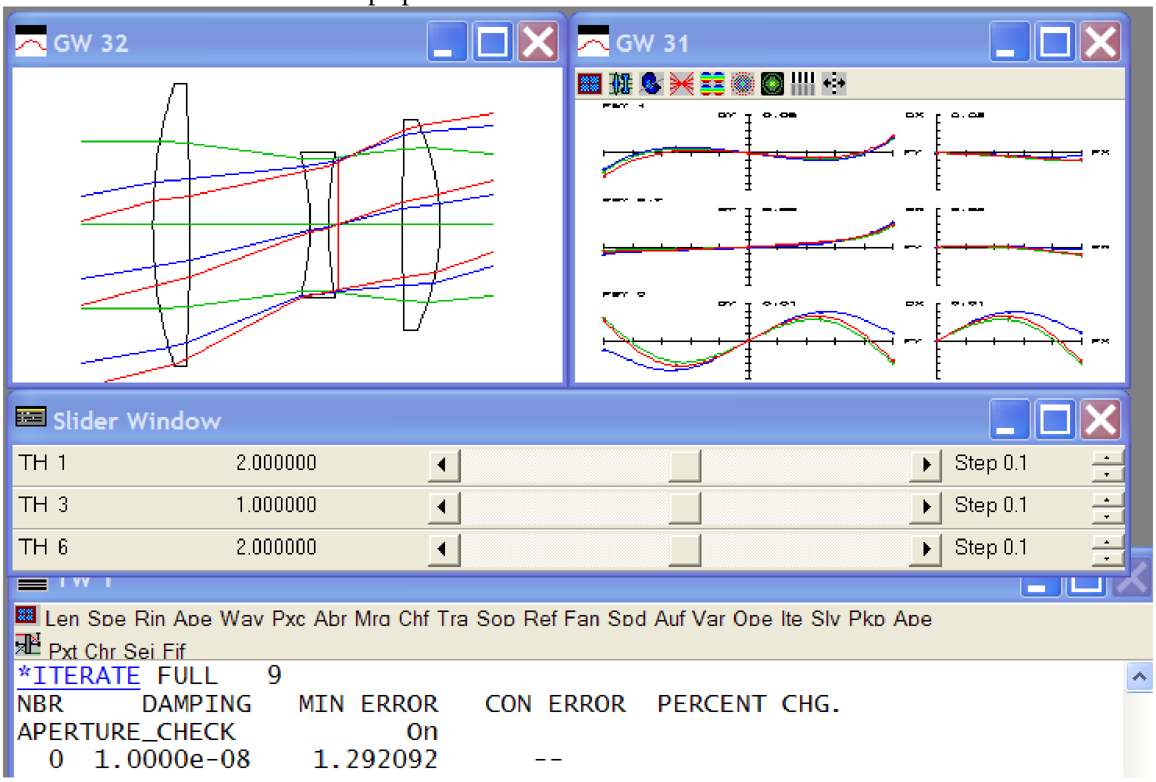
Rather than making these directly in the spreadsheet, they will be used to illustrate the process whereby adjustments can be made with simultaneous optimisation.

Slider-wheels with concurrent optimization on MTF

Adjusting lens thicknesses

The facility provided by OSLO to carry out slider-wheel optimization on one or more parameters, with a simultaneous callback to optimization on other variables, is a powerful design tool. In this context, note that no parameter adjusted with the slider-wheel bars should be an optimization variable. In the example given here, the slider-wheels will be used to adjust the lens thicknesses 1 for surfaces 1, 3 and 6, while the optimization on the lens curvatures, air spaces and image distance will continue to correct performance during each adjustment.

- Close the surface data spreadsheet.
- Open the slider-wheel spreadsheet.
- Select ⦿ **Ray-intercept curves** at ⦿ **All points** in the field.
- Define three sliders for **Thickness (TH) 1 Thickness (TH) 3** and **Thickness (TH) 6.**
- Select ⦿ **Enable sw_callback CCL function** with **Level** = **9** (This must be in the range from 1 to 9 to trigger the **Iter** function in the callback command.).
- Close the slider-wheel setup spreadsheet.



The text window, the slider-wheel bar and the two temporary slider-wheel windows, GW31 and GW32, should all be visible. The starting value of the error function is 1.292.

- Increase thickness 1 in steps of 0.1 until it reaches 4.0 giving an error function of 1.309.

- Increase thickness 3 in steps of 0.1 until it reaches 1.5. The error function will be 1.372
- Increase thickness 6 until it reaches 3.0; the error function becomes 1.408.
- Increase thickness 1 to 4.7 and thickness 6 to 4.7, the optimized error function will be 1.480.
- Close the slider wheels and list the lens.

```
*LENS DATA
50 mm f/5.6 +/-15 deg
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ        --         1.0000e+20    2.6795e+19              AIR

  1     29.485222 V    4.700000      8.263805 S            SK16 C
  2    -86.537346 V    6.170610 V    6.982274 S             AIR

  3    -15.359048 V    1.500000      3.947019 S              F4 C
  4     21.674799 V    0.498922 V    3.637632 S             AIR

 AST        --         2.252805 V    3.522903 AS            AIR   *

  6     77.234402 V    4.700000      4.546980 S            SK16 C
  7    -14.489037 V   44.432412 V    5.759546 S             AIR
IMS         --            --        13.376786 S
```

- Now to check the edge thicknesses, calculate the edge thickness of the front lens blank at a radius of 8.3+3.0 = 11.3 mm:

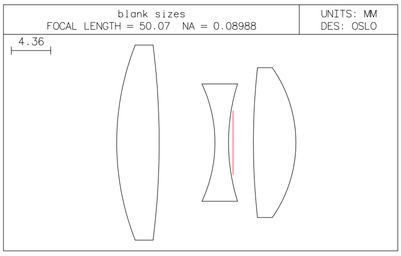
eth 1 2 11.3 11.3 0 0

giving a value of 1.7 mm.

- Also find the edge thickness of the third lens blank at a radius of 5.8+2.5 = 8.3 mm:

eth 6 7 8.3 8.3 0 0

which gives 1.6 mm.



These are both above the 1.5 mm which is required. For the diagram which shows the blank sizes, the barrel semi-diameters have been rounded upwards to 10 mm, 5.5 mm and 7.5 mm respectively.

Engineering aspects: ambiguity avoidance

It is extremely hard to tell which of the two surfaces of a nearly equi-concave lens is the steepest. To avoid assembly errors, we will investigate the effect of making the second lens truly equi-concave.

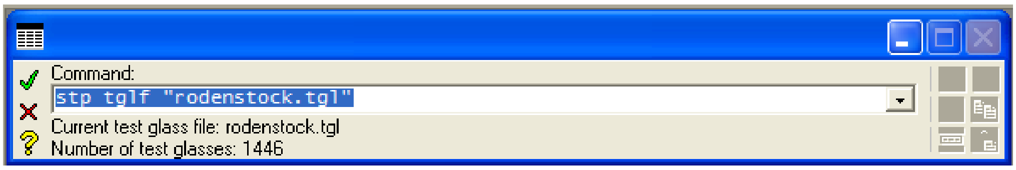
- Make the second element equi-concave. Click on the surface 4 gray RADIUS button and select **Minus curvature pickup (P)...** with **Pickup source surface** = **3 Pickup constant = 0, Pickup multiplir = 1.0**.

- Reoptimise. The error function is 1.640. This increase is acceptable.

```
*LENS DATA
50mm f/5.6 +/-15 deg
 SRF       RADIUS        THICKNESS   APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ         --        1.0000e+20    2.6795e+19             AIR

  1     26.647695 V     4.700000      8.681421 S            SK16 C
  2   -361.254520 V     7.067320 V    7.317984 S            AIR

  3    -18.435016 V     1.500000      3.907032 S             F4 C
  4     18.435016 P     0.499751 V    3.580456 S            AIR

 AST         --         2.398524 V    3.464412 AS           AIR    *

  6     42.567801 V     4.700000      4.577052 S            SK16 C
  7    -16.089048 V    43.427580 V    5.729062 S            AIR

 IMS         --            --        13.383518 S
```

Engineering aspects: testplate fitting

- Select the Rodenstock test glass file: Under the **File** menu header, select **Preferences > Set preference > Test_glass_file** and in the command line enter **rodenstock.tgl**.



This refers to an ASCII file **rodenstock.tgl** in the directory **OSLO/Prm64/bin/lmo/** which contains 1446 test glass values. Test glass files for other manufacturers are also available, and the user may create others in the same format if desired.

- Open the surface data spreadsheet.
- For surface 7 (the shortest radius at 16.09 mm) remove the variable curvature (change to **Direct specification**).
- Hold down the **shift** key and **left-click** the mouse twice on the radius. A value -16.0766 will appear as the nearest test glass, with a black box around it.
- Click on the green tick to accept this (or **shift-left-click** to restore the nominal radius). The letter **T** appears next to the fitted radius.
- Press **Ite** to optimize the remaining variables.
    - Repeat this sequence for surface 3 - remove the variable, fit the closest test glass, and optimise remaining variables.
    - Repeat this sequence for surface 6 and then again for surface 2.
    - Click on **Len** to list the design. Note the T which appears against each radius which has bees fitted to a test glass.

```
*LENS DATA
50 mm f/5.6 +/-15 deg
 SRF       RADIUS       THICKNESS   APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ         --        1.0000e+20    2.6795e+19             AIR

   1     26.699200 T    4.700000      8.692011 S          SK16 C
   2   -375.820000 T    7.098400 V    7.328991 S            AIR

   3    -18.438800 T    1.500000      3.907388 S            F4 C
   4     18.438800 P    0.499794 V    3.581367 S            AIR

 AST         --         2.384983 V    3.465615 AS           AIR   *

   6     42.322100 T    4.700000      4.572836 S          SK16 C
   7    -16.076600 T   43.429946 V    5.724953 S            AIR

 IMS         --            --        13.380875 S
```

- Click on **Ope** in the text window.

```
MIN RMS ERROR:     1.641164
```

The error function has risen slightly.

Rounding air spaces

Round the air spaces to avoid giving the impression that they are subject to tight tolerances:

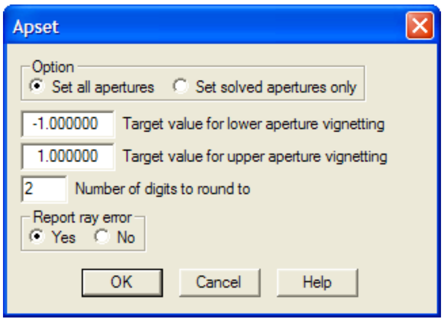
- Change thickness 2 to **`7.1`**, delete the variable and re-optimize.
- Change thickness 4 to **`0.5`**, delete the variable and re-optimize.
- Change thickness 5 to **`2.4`**, delete the variable and re-optimize on the one remaining variable, the focus.
- Enter the command: **`ope erf`**

The error function has risen slightly:

```
MIN RMS ERROR:     1.645251
```

Adjusting clear apertures

- Close the variables spreadsheet and the lens data spreadsheet.
- Under the **Optimize** menu header, select **Support routines > Vignetting > Set apertures** and in the dialog box change the number of digits to 2.



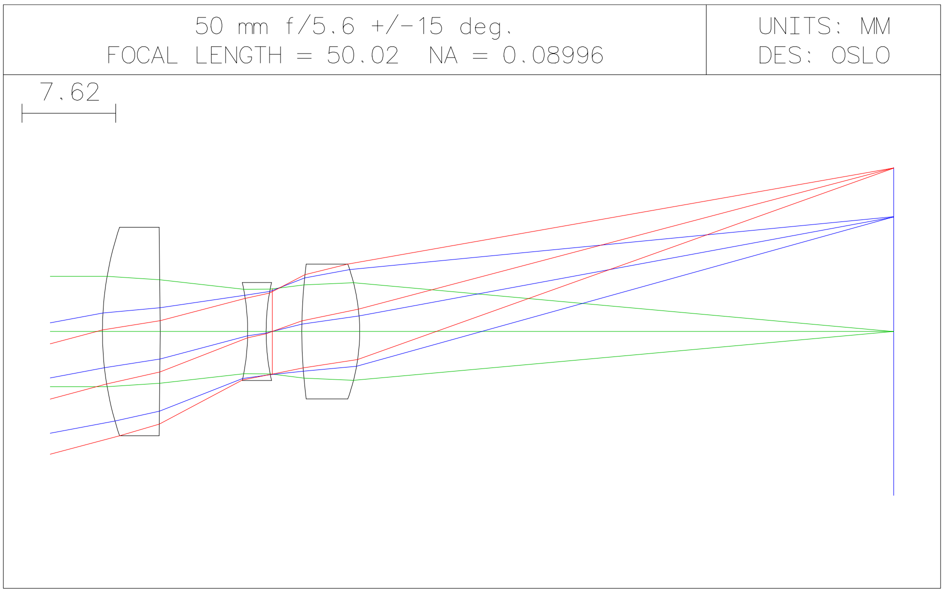
- Click on **OK**.

```
*APERTURES
 SRF    TYPE APERTURE RADIUS
  0      SPC   2.6795e+19
  1      SPC     8.500000   CHK
  2      SPC     8.500000
  3      SPC     4.000000
  4      SPC     3.600000
  5      SPC     3.500000   CHK
  6      SPC     5.500000
  7      SPC     5.500000   CHK
  8      CMP    13.380786
```

- Remove the **Checked aperture (K)** indications from surfaces 1, 5 and 7.

- Change the clear aperture surface 4 to 4.0 mm (as this lens is reversible).
- Remove the **Pickup (P)** from the radius on surface 4, change all the other radii to **Direct specification,** but leave the variable on the back focal distance (thickness 7).
- List the lens:

```
50 mm f/5.6 +/-15 deg.
 SRF       RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ         --         1.0000e+20    2.6795e+19             AIR

  1     26.699200        4.700000       8.500000            SK16 C
  2   -375.820000        7.100000       8.500000             AIR

  3    -18.438800        1.500000       4.000000              F4 C
  4     18.438800        0.500000       4.000000             AIR

 AST         --          2.400000       3.500000 A           AIR    *

  6     42.322100        4.700000       5.500000            SK16 C
  7    -16.076600       43.397798 V     5.500000             AIR

 IMS         --            --          13.366656 S                  *
```



This completes the design of this lens. The next chapter will start from this point as the basis of the tolerance calculation exercise.

Chapter 10 - Tolerances and drawings

50 mm f/5.6 objective: specification

For the lens which is the final design of the triplet describes in the previous section, the task is to define the surface and component tolerances which, based on root-sum-of-squares statistics, give an MTF which does not fall below 0.1 at 30 cycles/mm at any of the three field points. The assumption will be made that in production there will be a uniform distribution of errors within the tolerance band, and that a focus adjustment will be carried out on assembly.

This will be accomplished using a CCL command which assesses the MTF at 30 cycles/mm in both azimuths at 5 field points across the field - with values of FBY of 0.0, ± 0.7 and ± 1.0.

Defining the tolerance error function:"opcb_dmtf"

The CCL routine below will calculate the MTF in 2 azimuths at 5 field points, 10 values in all. It will then identify the worst (i.e. lowest) of these, and subtract it from the diffraction limited MTF at the same frequency. The error function consists of a single operand, having this value.
Subtracting the lowest MTF from the ideal ensures that, as in all optimization operands, the system with the lowest value of the error function is the best one.
The routine here is a "callback" - that is to say, it is evaluated whenever the error function is calculated. It places a single value into the real array **ocm[1]**. This value is then called using the string **OCM1** as the definition of the operand.

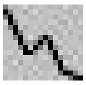
- Open the text editor and create a new file:

```
//
// Written by [your name] [Date]
//

cmd opcb_dmtf(void)

// hlp:   <P>Callback for DMTF (degradation in MTF) optimization.
// hlp:   OCM1 is max reduction in MTF below ideal MTF at 5 field
// hlp:   points for one spatial frequency. Both X & Y are included
// hlp:   on axis, as well as field height FBY both +ve and -ve.</P>

{
        static double mtfs[10],diff_lim,mtf_min;
        static double sf=30.0; //spatial frequency

        stp outp off;
        k=sbrow;
        sbr k 1;//scrolls spread sheet buffer to preserve contents

                sop(0,0,0);
                mtf(tfr,chr,y,sf,sf,0);
                mtf(tfr,chr,x,sf,sf,0);

                sop(0.7,0,0);
                mtf(tfr,chr,y,sf,sf,0);
                mtf(tfr,chr,x,sf,sf,0);

                sop(-0.7,0,0);
                mtf(tfr,chr,y,sf,sf,0);
                mtf(tfr,chr,x,sf,sf,0);
```

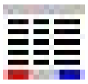
```
                sop(1,0,0);
                mtf(tfr,chr,y,sf,sf,0);
                mtf(tfr,chr,x,sf,sf,0);

                sop(-1,0,0);
                mtf(tfr,chr,y,sf,sf,0);
                mtf(tfr,chr,x,sf,sf,0);

                diff_lim=d5;

                if(diff_lim==0) cclabort("Diff limited MTF zero","opcb_dmtf");

                mtfs[0]=b5;//  Ax T
                mtfs[1]=b8;//  AX S
                mtfs[2]=b14;// +7 T
                mtfs[3]=b17;// +7 S
                mtfs[4]=b23;// -7 T
                mtfs[5]=b26;// -7 S
                mtfs[6]=b32;// +1 T
                mtfs[7]=b35;// +1 S
                mtfs[8]=b41;// -1 T
                mtfs[9]=b44;// -1 S

                mtf_min=1.0;
                for(i=0;i<10;i++)if(mtfs[i]<mtf_min)mtf_min=mtfs[i];

                ocm[1]=diff_lim-mtf_min;// DMTF: MAX FALL BELOW DIFFRACTION LIMIT


        sbr -k 0;
        stp outp on;
}
```

- Save the command in **/private/ccl/** with the name **optim_dmtf.ccl**, and check correct compilation.

```
*CCL COMPILATION MESSAGES:
 No errors detected
```



- Open the optimization conditions spreadsheet.
- Change the entry for the optimization callback, **Command for CCL/SCP operands: opcb_dmtf**
- On the bottom line, under **Error function value**, select ⦿ **Root-mean-square (RMS).**
- Close the optimization conditions spreadsheet.
    - Enter the command line **ope new;end** to delete the existing operand list**.**



- Open the operands data editor spreadsheet.
- Fill in the name and definition as in the following table:

OP	MODE	WGT	NAME	DEFINITION
1	MIN	1.000000	DMTF at 30	OCM1

- Close the operands spreadsheet and list the operands with **Ope**

```
*OPERANDS
 OP  MODE    WGT      NAME           VALUE   %CNTRB DEFINITION
O 1    M    1.000000 DMTF at 30    0.408358 100.00 OCM1
MIN RMS ERROR:      0.408358
```

Since there is only one operand in the error function, the value of the RMS minimization error is the actual value of DMTF, the degradation in MTF.

Defining the compensator

To enable the widest possible tolerances to be assigned to the lens, one or more "compensators" can be defined. These represent the adjustments made during assembly which can partly compensate the errors in the individual components. The most common compensator is, of course, the focus, and that is the only compensator used in this example.

To define a compensator, the parameter concerned must be defined as an optimization variable.

- In the text window click on **Var.**
- Confirm that thickness 7 is variable, and is the only variable.

Before commencing the calculation of tolerances, the compensator must be set to the optimum position for the nominal design.

Optimizing on the compensator

- To find the best focus, just optimize with **Ite** and click on **Var**

```
*ITERATE FULL  10
NBR      DAMPING    MIN ERROR    CON ERROR   PERCENT CHG.
  0  1.0000e-08     0.408358        --
  1    6.158000     0.367641        --         9.970860
  2   61.580000     0.361620        --         1.637656
  3  379.209640     0.360640        --         0.271130
  4  379.209640     0.360640        --           --
  5  379.209640     0.360640        --           --

*VARIABLES
 VB    SN  CF   TYP        MIN          MAX          DAMPING       INCR         VALUE
V 1     7   -   TH      0.100000   1.0000e+04     1.000000     0.000450     43.385935
```

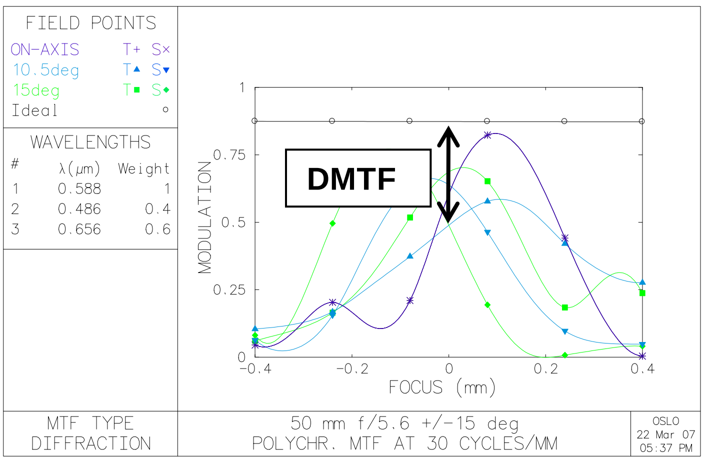
To confirm the choice of focal plane, plot the through-focus MTF at 30 cycles/mm:

- Click on the icon and accepting all defaults.

- Right click in the graphics window, and select **Recalculate with new parameters...**
- Enter **Frequency 30** cycles/mm.

The curves show that the ideal focal plane has been chosen.

The diagram also illustrates the significance of the quantity DMTF. It is the largest drop below the diffraction limit at any of the five field points, with assessment in both sagittal and tangential directions (including on axis). This error function has been chosen so that asymmetric tolerances can be included in the calculation.



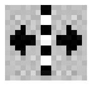
- Under the **Evaluate** menu header, select **Transfer function > Print/Plot OTF** and in the dialog box select: **Monochromatic, Print function**, with **Maximum frequency** = **30** line pairs per mm.

In this case the diffraction limit MTF at 30 cycles/mm is 0.86. At the best focus, the nominal value of the worst MTF at 30 cycles/mm is 0.49, giving a value of DMTF for the nominal system of 0.36. If the MTF must remain everywhere above 0.1, the value of DMTF must not increase to more than 0.76.

Calculating decenter tolerances

As an example we will calculate the effect of decentering the second lens by the minimum amount one can expect from traditional mounting methods:

- Open the surface data spread sheet.
- Under **Special** for surface 3, select **Coordinates (C)**.
- Enter **.075** mm for **DCY,** and under Use base coordinates for returns to this surface: select **Yes.**
- Under **Special** for surface 4, select **Coordinates (C)**.
- Under Coordinate return: select **Yes** and under Return to surface: enter **3**
- Click on **Ope** and find the new DMTF value:



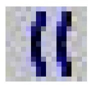
```
MIN RMS ERROR:     0.612975
```

So DMTF has increased from 0.36 to 0.61, an increase of 0.25. This has used more than half the entire tolerance budget of 0.40 on one error, so clearly a specialized mounting method (such as laser centering in the mount) will need to be used to meet the performance target. That being the case, we will assume that all the component decenter tolerances can be regarded as zero, and calculate the budget for the remaining errors.

Checking tolerance entries

The default tolerance values assigned to each parameter are the ISO10110 values. Because there are two successive air spaces (4 and 5), the tolerance on the first one can be removed.

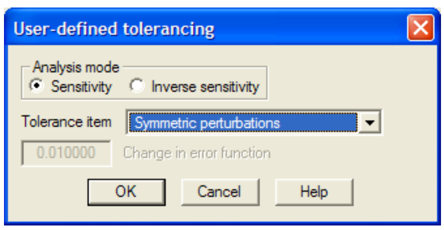
- Click on the Edit Surface Tolerances icon, or select from the menu header **Tolerance > Update tolerance data > Surface.**



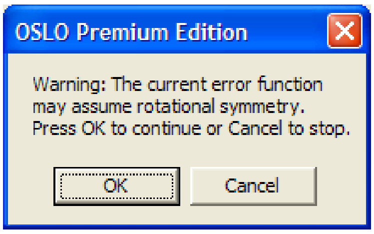
- Click on **Display all surfaces tolerances: ⦿ Yes.**
- For surface **4,** set **TH TOL** (thickness tolerance) to **0.0**
- Close the surface tolerances data editor.

Symmetrical tolerances surface calculation

- From the menu header select **Tolerance > User-defined Tolerancing** and select **Sensitivity** and **Symmetric perturbations.**



- A warning message comes up. The error function does not assume rotational symmetry, so click on **OK.**



The sensitivity analysis (which may take one or two minutes) lists 6 power errors, 3 element thicknesses, 2 air spaces, 3 indices and 3 V-values, 17 symmetrical contributions in all. The summary is:

	UNCOMPENSATED	COMPENSATED
WORST CASE CHANGE	6.019989	3.022531
STANDARD DEVIATION		
RSS	1.659396	1.056369
UNIFORM	0.958053	0.609895
GAUSSIAN	0.729824	0.464604

The change in the error function, with focus compensation, for a uniform distribution of errors within the tolerance band is 0.61 is an indication that the standard tolerances are not acceptable.

If we allocate 0.33 of the budget of 0.40 to the symmetrical tolerances, then each tolerance will be allowed 0.33/√17 = 0.08 MTF degradation.

- From the menu header select **Tolerance > User-defined Tolerancing** and select **Inverse sensitivity** and **Symmetric perturbations,** enter **0.08** for **Change in error function.**

```
*INVERSE SENSITIVITY ANALYSIS
 ERROR FUNCTION FOR NOMINAL SYSTEM:    0.360640
 ALLOWED CHANGE IN ERROR FUNCTION:     0.080000
```

POWER ERROR TOLERANCE

SRF	ALLOWED TOLERANCE UNCOMPENSATED	COMPENSATED
1	4.204420	109.362285
2	4.416476	72.560814
3	1.941512	1.807345
4	1.910946	1.747543
6	3.571230	3.882230
7	3.599738	27.941716

These tolerances must be tightened from the ISO10110 values of 10, 10, 5, 5, 10 and 10 fringes to 5 fringes throughout.

ELEMENT THICKNESS TOLERANCE

SRF	ALLOWED TOLERANCE UNCOMPENSATED	COMPENSATED
1	0.074299	0.096090
3	0.079866	0.246151
6	0.109412	0.337794

The first one needs to be changed to from the ISO10110 value of 0.2 to 0.1 mm.

AIR SPACE TOLERANCE

SRF	ALLOWED TOLERANCE UNCOMPENSATED	COMPENSATED
2	0.079453	0.053990
5	0.035223	0.036388

These must be tightened to 0.05 mm.

INDEX OF REFRACTION TOLERANCE

SRF	ALLOWED TOLERANCE UNCOMPENSATED	COMPENSATED
1	0.000460	0.006810
3	0.000381	0.000346
6	0.000376	0.000342

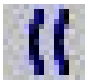
These must all be tightened from .001 to 0.0006 (note that the glass type for lens 1 and for lens 3 are the same, so only one standard of glass need be procured).

ABBE V-NUMBER ERROR (IN %) TOLERANCE

SRF	ALLOWED TOLERANCE UNCOMPENSATED	COMPENSATED
1	5.230509	20.247082
3	3.291042	12.443420
6	4.223386	14.964191

These can stay at 0.8%.

Updating symmetrical surface tolerances



- Click on the Edit Surface Tolerances icon, or select from the menu header **Tolerance > Update tolerance data > Surface.**
- Change the tolerances on symmetric form error (**PWR FR**) at all surfaces to **5**
- Change the tolerances on thickness (**TH TOL**) at surfaces 2 and 5 to **0.05.**
- Change the tolerance on thickness (**TH TOL**) at surfaces 1 to **0.1**
- Change the tolerances on index (**RN TOL**) at surfaces 1 3 and 6 to **0.0006**.
- Close the surface tolerances data editor.
- Repeat the sensitivity calculation for symmetrical tolerances:

STATISTICAL SUMMARY

	UNCOMPENSATED	COMPENSATED
WORST CASE CHANGE	4.548071	0.744409
STANDARD DEVIATION		
RSS	1.271472	0.472209
UNIFORM	0.734085	0.272630
GAUSSIAN	0.559210	0.207684

COMPENSATOR STATISTICS

COMP		MEAN	STD DEV	MAX	RSS
TH	7	-0.011420	0.099581	0.356100	0.483578

- The degradation of 0.27 (less than the 0.33 allowed for) leaves a balance of 0.13 for the asymmetric tolerances.

Asymmetric tolerances surface calculation

Since the full asymmetrical sensitivity analysis cannot be undertaken with OSLO EDU, the relevant elements of the sensitivity analysis will be calculated separately.

There are only two surface errors to be considered. These consist of 6 surface irregularity errors, and 6 surface tilt errors (TLA only), 12 in all. If we allocate the remaining 0.13 of MTF degradation (that is, the budget of 0.4 minus the 0.27 taken up by symmetrical tolerances) to these 12 tolerances, then each contribution is $0.13/\sqrt{12} = 0.038$.

- Remove the variable from thickness 7 – focus cannot compensate for asymmetrical errors.
- Remove the variable from thickness 7, since focus cannot compensate for asymmetrical errors.
- From the menu header select **Tolerance > User-defined Tolerancing** and select **Inverse sensitivity** and **Irregularity fringes,** enter **0.038** for **Change in error function.**

```
*INVERSE SENSITIVITY ANALYSIS
 ERROR FUNCTION FOR NOMINAL SYSTEM:     0.360640
 ALLOWED CHANGE IN ERROR FUNCTION:      0.038000

 IRREGULARITY ERROR TOLERANCE
       ALLOWED TOLERANCE
 SRF     UNCOMPENSATED
  1         2.097225
  2         2.261429
  3         0.816355
  4         0.818204
  6         1.263006
  7         1.188189
```

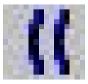
The tolerance on both surfaces of the last lens needs to be changed to from the ISO10110 value of 2 fringes to 1 fringe.

- From the menu header select **Tolerance > User-defined Tolerancing** and select **Inverse sensitivity** and **Surface tilt tolerance (TLA),** and again enter **0.038** for the **Change in error function.**

```
*INVERSE SENSITIVITY ANALYSIS
 ERROR FUNCTION FOR NOMINAL SYSTEM:     0.360640
 ALLOWED CHANGE IN ERROR FUNCTION:      0.038000

 SURFACE TILT TOLERANCE (TLA)
       ALLOWED TOLERANCE
 SRF     UNCOMPENSATED
  1         0.139481
  2         0.108784
  3         0.145052
  4         0.161710
  6         0.153277
  7         0.110764
```

All these tilt tolerances must be changed to 0.08 degrees (5 minutes).

Updating asymmetric surface tolerances



- Click on the Edit Surface Tolerances icon, or select from the menu header **Tolerance > Update tolerance data > Surface.**
- Change the tolerances on irregularity – i.e. asymmetric form error **IRR FR** - at surfaces 6 and 7 to **1.0**
- Change the tolerances on tilt (**TA TOL**) for all refracting surfaces to **0.1**
- Close the surface tolerances data editor.

Updating asymmetric component tolerances

The decision has already been made to center the components precisely.

- Select from the menu header **Tolerance > Update tolerance data > Component.**
- Change the tolerances on centration (**DCY**) and tilt (**ALPHA**) to **0.0**

Asymmetric tolerances calculation

- From the menu header select **Tolerance > User-defined Tolerancing** and select **Sensitivity** and **Asymmetric perturbations,** or type the command: **tsn asy.** Only the summary data is given here.

```
STATISTICAL SUMMARY
                        UNCOMPENSATED
 WORST CASE CHANGE         0.946050
 STANDARD DEVIATION
     RSS                   0.308895
     UNIFORM               0.178341
     GAUSSIAN              0.135856
```

- The degradation of 0.18 is a little larger than the 0.13 budget for the asymmetric tolerances, but note that all tolerance calculations subject to the approximations of statistics.

Tolerance data listing

- From the **Lens** menu header select **Show tolerance data > Surface.**

```
*SURFACE TOLERANCES
50 mm f/5.6 +/-15 deg
      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   26.6992   --    5.00  2.00   4.7000 0.1000      SK16 0.0006   --   0.0800
        --      --                   --     --              0.8000   --   0.0800

  2 -375.8200   --    5.00  2.00   7.1000 0.0500       AIR   --     --   0.0800
        --      --                   --     --                --     --   0.0800
 -----------------------------------------------------------------------------
  3  -18.4388   --    5.00  1.00   1.5000 0.1000        F4 0.0006   --   0.0800
        --      --                   --     --              0.8000   --   0.0800

  4   18.4388   --    5.00  1.00   0.5000   --         AIR   --     --   0.0800
        --      --                   --     --                --     --   0.0800
 -----------------------------------------------------------------------------
  5     --      --     --    --    2.4000 0.0500       AIR   --     --     --
        --      --                   --     --                --     --     --
 -----------------------------------------------------------------------------
  6   42.3221   --    5.00  1.00   4.7000 0.2000      SK16 0.0006   --   0.0800
        --      --                   --     --              0.8000   --   0.0800

  7  -16.0766   --    5.00  1.00  43.3859   --         AIR   --     --   0.0800
        --      --                   --     --                --     --   0.0800
 -----------------------------------------------------------------------------
  8     --      --     --    --      --     --                       --     --
        --      --                   --                              --     --
 FRINGE WAVELENGTH:    0.546070
   Fringes measured over clear aperture of surface unless indicated.
   Tilt tolerances are specified in degrees.
```

- From the **Lens** menu header select **Show tolerance data > Component.**
- All values in this table should be zero.

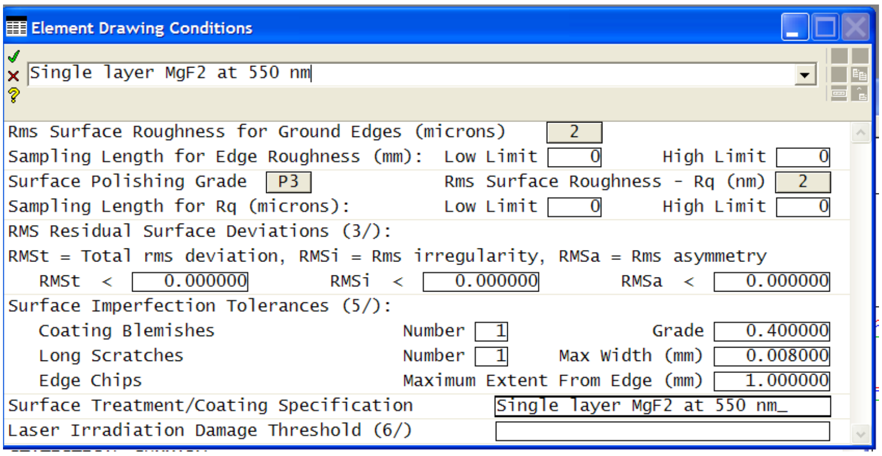
ISO 10110 component drawing

The middle element of the triplet objective will be used to demonstrate this facility.

Setting element drawing defaults

- From the menu header select **Lens > Lens Drawing > Element drawing conditions** or type the command: `edd`

- Set **RMS surface roughness for ground edges R$_q$** = **2** (microns) `medium.`
- Set **RMS surface roughness R$_q$** = `2nm (medium)`
- Set **Surface polishing grade** to **P3**.
- Set **Coating blemishes** to **1** **Grade** **0.4**. (MIL 80-50 equivalent)
- Set **Long scratches** to **1** **Width** **0.008 mm** (MIL 80-50 equivalent)
- Set **Edge chips: Maximum extent from edge** to **1 mm**.
- Define **Coating specification** as `Single layer MgF2 550 nm`.

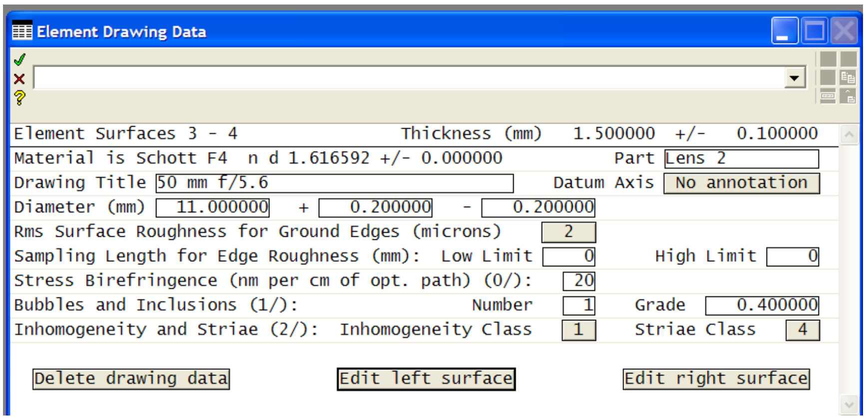


- Close the spreadsheet.

Setting element material properties

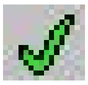
- From the menu header select **Lens > Lens Drawing > Element**
- For **Left surface of element** select **3**
- Fill in:
  - **Part** `Lens 2 [date]`
  - **Drawing title** `50 mm f/5.6`
  - **Diameter** `11 mm +0.2/-0.2`

- **Stress birefringence (0/):** **20**
- **Bubbles and inclusions (1/) Number 1 Grade 0.4**
- **Striae Class 4.**

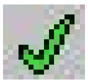


Setting element surface properties

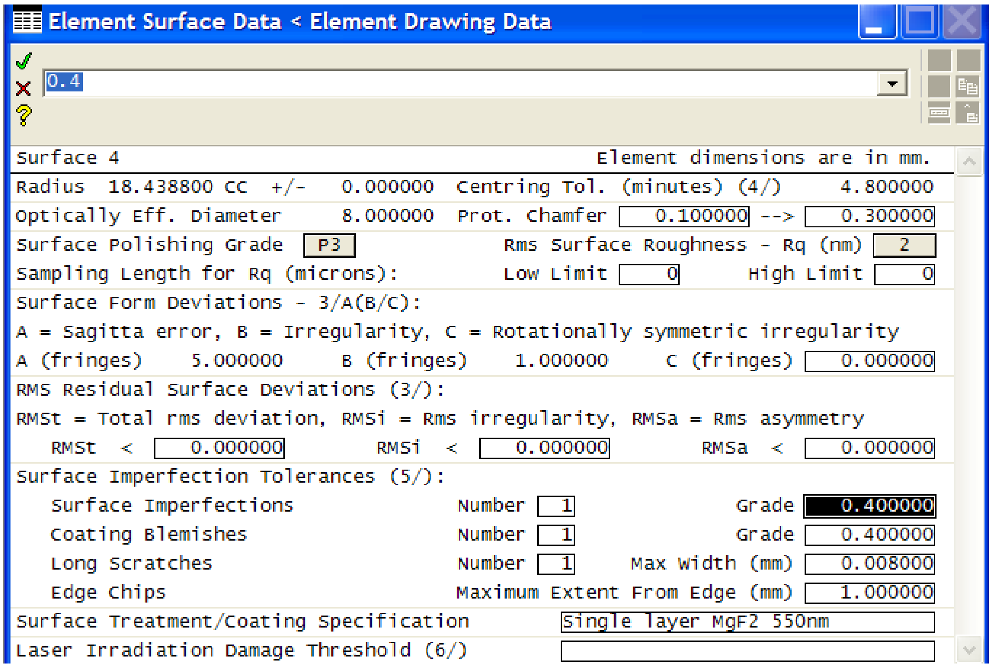
- Click on **Edit left surface.**
- Leave most entries unchanged but fill in:
  - **Surface imperfections Number 1 Grade 0.4**



- Click on the green tick to close the spreadsheet.
- Click on **Edit right surface.**
- Again fill in:
  - **Surface imperfections Number 1 Grade 0.4**



- Click on the green tick twice and the drawing appears.

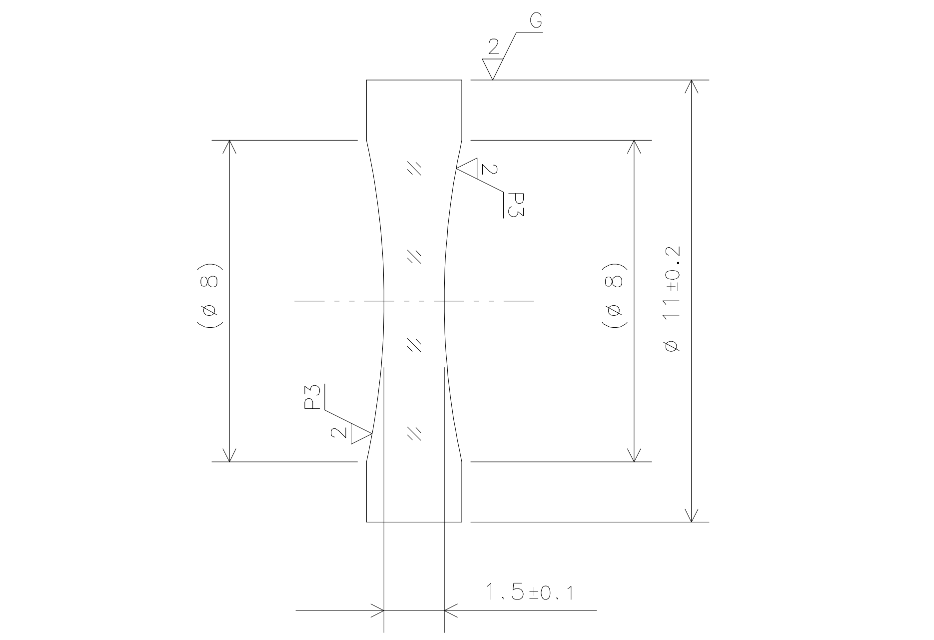


ISO 10110 component drawing

Element drawing

The message appears in the message area:

`Element drawing is best viewed in a "portrait window" format.`



Left Surface:	Material Specification:	Right Surface:
R 18.4388 CC øe 8.0 Prot. Cham. 0.1 - 0.3 (λ) Single layer MgF2 550nm 3/ 5(1) 4/ 4.8' 5/ 1x0.4; C 1x0.4; L 1x0.008; E 1.0 6/ -	Schott F4 n d 1.616592±0.0006 v d 36.63±0.8% 0/ 20 1/ 1x0.4 2/ 1;4	R 18.4388 CC øe 8.0 Prot. Cham. 0.1 - 0.3 (λ) Single layer MgF2 550n 3/ 5(1) 4/ 4.8' 5/ 1x0.4; C 1x0.4; L 1x0.008; E 1.0 6/ -

50 mm f/5.6		your_company_name your_street_name your_town
Lens 2 [date]	Ind. acc. ISO 10110	

Appendix 1 - Index of lens data commands

This table gives an alphabetic listing of the principal commands used in lens data input that can be found in the OSLO Program Reference manual. The letter in the second column is the label shown on the gray button in the surface data spreadsheet when the relevant parameter is set. Note that not all of these commands are available in OSLO EDU.

Command		Explanation
ach	F	array chan
ad	A	aspheric
ae	A	aspheric
af	A	aspheric
afo		afocal mode
ag	A	aspheric
air		medium
al	S	aplanatic slv
alc	S	aplanatic slv
amo		abn mode
ang		field angle
ap		aperture
apck		ap checking
apn	X	special ap
ary	F	lens array
as0, as1, *etc*.	A	aspheric
asi	F	alt srf intersec
ast	A	aperture stop
asp	A	aspheric
ben	C	tilt & bend
bry		birefringent
cak	B	crystal axis
cal	B	crystal axis
cam	B	crystal axis
cc	A	conic const
cfg		oonfiguration
cns	A	cone
csd		slv delete
cslv		slv in alt cfgs
ctf	T	test glass cv
cv		curvature
cvx	A	toric
dcx	C	decentre
dcy	C	decentre
dcz	C	decentre
del		srf delete
des		desgr name
dlid,dlfd,dlha,dlva, dlfs,dlls,dlap,dlrs, dlnr *etc*		lens and ray drawing control
doe	D	diffractive
drw		srf drawing
ebr		ent beam rad
ec	S	edge slv
eik	E	eikonal srf
end		end data
epxy		ray aiming
esd	E	eikonal del
fno		F number
frn	F	Fresnel
gc	C	global coord
gcs	C	glob ref srf
gdt	G	gradient index
gih		image height
gla		medium
gor	D	grating order
grd	G	gradium
grp		group
gsp	D	grating spc
hor	D	hologram order
idd	Z	zernike
ims		image srf
ins		srf insert
itf	I	interferogram
inv		srf invert
jsd	Z	polarisation
kco	D	kinoform order
kdp	D	kinoform depth
ldp	F	srf dwg pen
len		begin data
lid		lens identifier
lme		module end
lmo		module begin
lse		spreadsheet
mco	M	coating
mer		insert lens
merge_catalog		insert catalog lens
nac	Q	non-sequential
nao		obj space NA
nap		im space NA
not	N	surface note
nxt		next srf
obh		object height
opdw		OPD in waves
pfl	L	perfect lens
pfm	L	perfect lens

In this table, S refers to solves, C refers to tilt/decenter coordinates, and A refers to aspheric surfaces. Other letters are the flags used in the spreadsheet. A complete listing of the lens data commands is in the OSLO Program Reference. These commands may be used:

1. In the command window, explicitly, as part of an update process:

```
len upd
gto 2
nxt
th 1.0
end
```

Note the use of `gto, nxt, end`. A semicolon has the same effect as `nxt.`

2. As part of a CCL command:

```
{
len upd;
gto(3);
th(1.0);
end;
}
```

Note the semicolons at the end of each line.

3. In the command window, as a self-contained command:

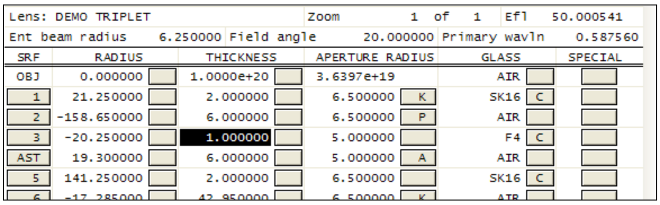
```
th 3 1.0
```

This is called “global editing”

4. As part of a lens file:

```
NXT  //SRF 3
...
TH   1.0
```

5. Implicitly, when the spreadsheet is updated, as shown here.



Lens: DEMO TRIPLET | Zoom 1 of 1 | Efl 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		3.6397e+19		AIR		
1	21.250000		2.000000		6.500000	K	SK16	C	
2	-158.650000		6.000000		6.500000	P	AIR		
3	-20.250000		1.000000		5.000000		F4	C	
AST	19.300000		6.000000		5.000000	A	AIR		
5	141.250000		2.000000		6.500000		SK16	C	
6	-17.285000		42.950000		6.500000	K	AIR		

Appendix 2 - Graphics reference

Alphabetical index

KEY TO COMMAND REFERENCE (in order of preference)

Standard tools	Accessed via graphics window toolbar using the icon shown
Advanced Analysis	Accessed via main window toolbar using the icon shown
Tools > Special	Accessed via main window menu headers
`grindex`	CCL command accessed via the command line

Function	Command Reference	Icon	OSLO version	Grid
2D-waveguide coupling	*Tools > Special > 2D*	-	Prm	e10
Astigmatism - S & T over field	*Evaluate > Ray Fans*	-	All	d11
Axial chromatic focal shift	Ray Analysis		All	h2
CCL example - 4 graphs	*Tools > Plotting*	-	All	h9
CCL example - contour	*Tools > Plotting*	-	All	b10
CCL example - map	*Tools > Plotting*	-	All	c10
CCL example - pen colours	*Tools > Plotting*	-	All	d10
CCL example - XY graph	*Tools > Plotting*	-	All	d10
Distortion grid plot	Ray Analysis		All	b3
Distortion at all wavelengths	*Evaluate > Ray Fans*	-	All	e11
Doublet - slider-wheel design	*Tools > Demos*	-	All	h1-
Draw system 2D	Lens Drawing		All	a1
Draw system 2D	Standard tools		All	a1
Draw system 3D shaded solid	Lens Drawing		All	d1
Draw system 3D solid	Lens Drawing		All	c1
Draw system 3D variable view	Lens Drawing		All	e1
Draw system 3D wire-frame	Lens Drawing		All	b1
Draw system 3D wire-frame	Standard tools		All	b1
Draw system - conditions	Lens Drawing		All	--
Draw system - zoom lens	Lens Drawing		Prm	h1
Element drawing	Lens Drawing		All	a2
Encircled energy - diffraction	Energy		All	b7
Encircled energy - geometrical	Energy		All	e7
Ensquared energy - diffraction	Energy		All	c7
Ensquared energy - geometrical	Energy		All	f7
Extended source image	**Extended Source**		All	e9
Footprint - one field point	Spot Diagram		All	e4
Footprint profile - all field points	Spot Diagram		All	f4
Gaussian beam movie	*Tools > Demos*	-	All	g10

Ghost image movie	Spot Diagram		Prm	g4
Glass catalogue n-V map	*Lens >Glass Catalog*	-	All	a9
GRIN lens - slider-wheel design	*Tools > Demos*	-	Prm	b11
GRIN axial index	**grindex**	-	All	-
Internal transmittance of glass	**internal_trans**	-	All	-
Incidence angle statistics	**iangstat**	-	All	h11
Lateral chromatic aberration	Ray analysis		All	a3
Lateral colour (pri & sec)	*Evaluate >Ray Fans*	-	All	-
Longitudinal aberration	*Evaluate >Ray Fans*	-	All	c11
LSF/KED - diffraction calc	Energy		All	d7
LSF/KED - geometrical calc	Energy		All	g7
MTF over field - 3 frequencies	MTF		All	d6
MTF - one field point	MTF		All	a6
MTF square wave - 1 field point	MTF		All	e6
MTF - thru frequency report	MTF		All	h5
MTF - thru frequency report	Standard tools		All	h5
MTF and spot size thru focus	MTF		All	f6
MTF FFT one field point	MTF		Prm	b6
MTF thru focus - one field point	MTF		All	h6
MTF thru focus across field	MTF		All	a7
MTF thru focus report	MTF		All	g6
MTF thru focus report	Standard tools		All	g6
OPD - 2D field points	Ray Analysis		Prm	g2
OPD - one field point	Ray Analysis		All	f2
OPD contour - one field point	Wavefront		All	f3
OPD interferogram	Wavefront		All	g3
OPD map - 2D field points	Wavefront		Prm	d3
OPD map - one field point	Wavefront		All	e3
OPD map/contour report	Wavefront		All	c3
OPD map/contour report	Standard tools		All	c3
OPD report	Ray Analysis		All	e2
Optimization ray set	Spot Diagram		Prm	h4
Partial coherence - bar image	**Advanced Analysis**		All	g9
Photometric plot	**ridemo**	-	All	f11
Pixellated image	**Extended Sources**		All	f9
Polarisation map	Polarization		Prm	b8
PSF - 2D contour lines	*Evaluate > Spread fn*	-	Prm	b9
PSF - 2D field points	PSF		Prm	b5
PSF - contour	PSF		All	c5
PSF - FFT - contour	PSF		All	e5
PSF - FFT - one field point	PSF		All	f5
PSF - one field point	PSF		All	d5

PSF - section	PSF		All	g5
PSF report	PSF		All	a5
PSF report	Standard tools		All	a5
PTF - thru frequency	MTF		All	c6
Public lens database	*File> Lens Database*	-	All	h8
Ray analysis - 2D field points	Ray Analysis		Prm	d2
Ray analysis - one field point	Ray Analysis		All	c2
Ray analysis report	Ray Analysis		All	b2
Ray analysis report	Standard tools		All	b2
Ray analysis SIGMA format	**repsig**	-	All	g11
Ray bundles 2D	Lens Drawing		All	f1
Ray bundles 3D	Lens Drawing		All	g1
Ray bundles movie	**fieldscan**	-	Prm	h1
RMS spot size & RMS OPD	Spot Diagram		All	d4
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Tabular graphics command reference

See below.

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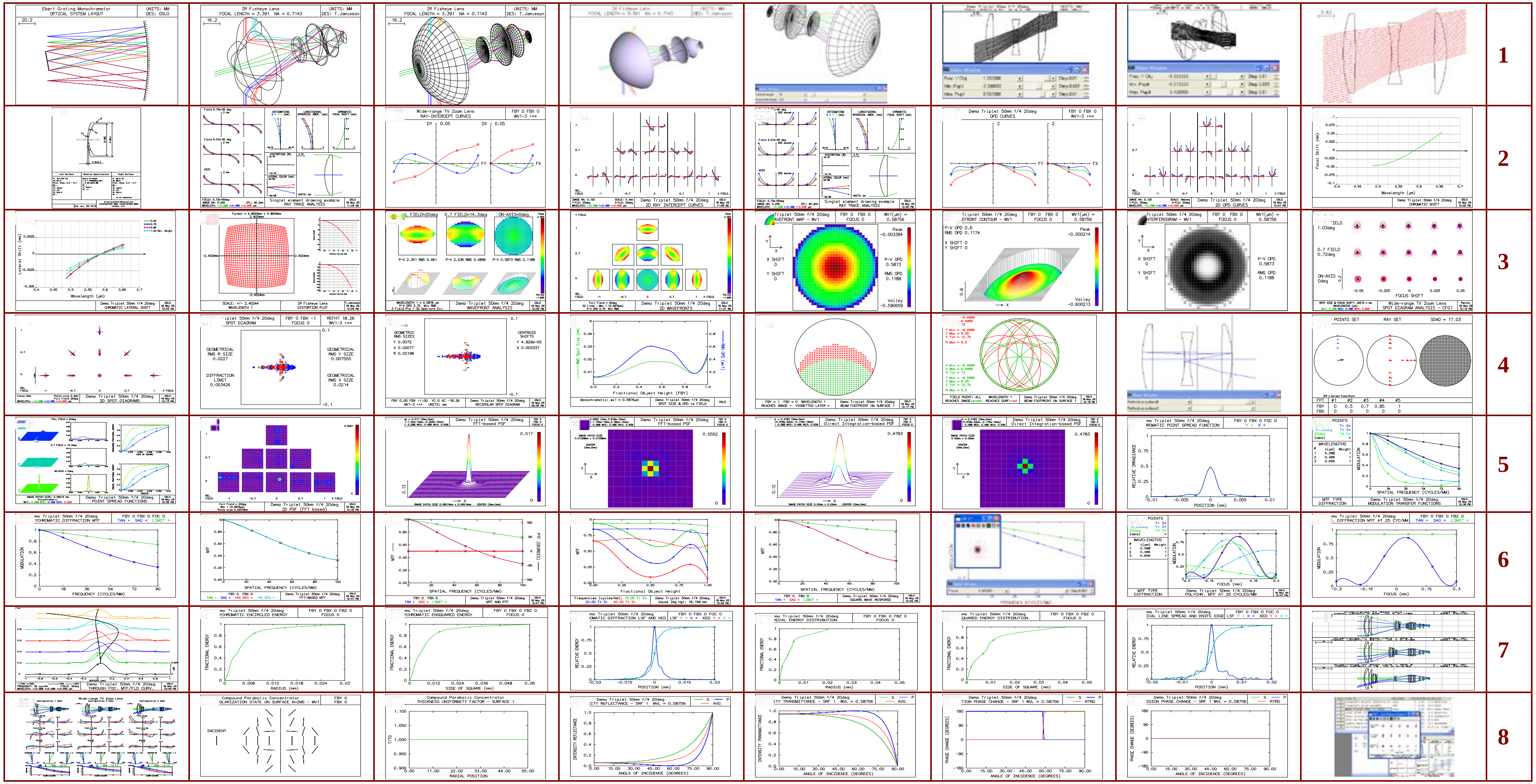
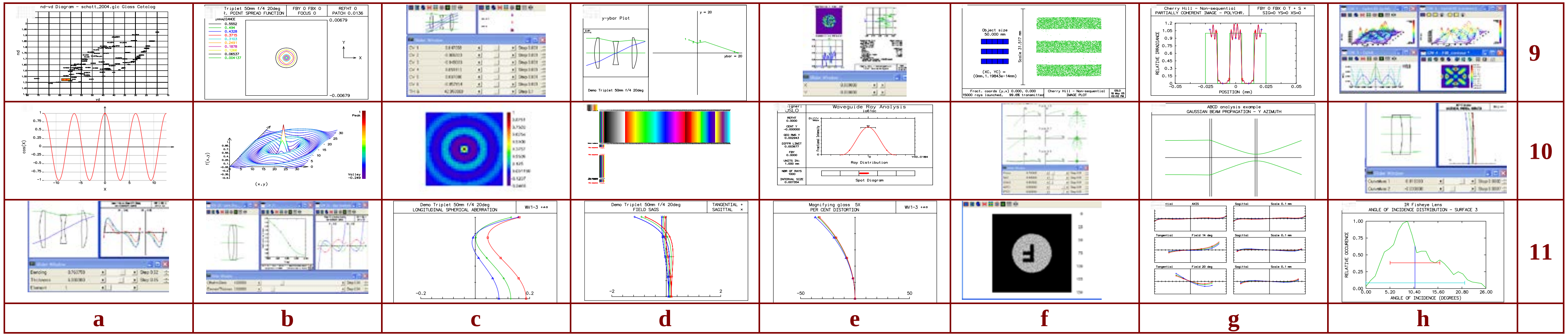
The 88 examples of OSLO graphics shown in the table below represent almost the full range of graphics output available to users of OSLO Premium version. Brief descriptions of each graphic example are given above. The routes for accessing these graphics are listed in the tabular command reference with the following format:

`OSLO commands`	These are given in short form only. They can be typed as shown, and they are also useful as an index to the HELP facility.
Standard Tools	These refer to the groups of icons called up from the top left corner of any graphics window
ExtendedSources	These refer to the groups of icons called up from the top left corner of the main window.
Evaluate>Spread Fn	These show how most of the graphs can be created from menu headers.

* Graphs indicated are for one field point only, and they can give results only on axis if accessed via the icons. To plot individual graphs for other field points, either issue the set object point command and then use the command line (for example `sop 1 0 0;plr`), or work through the menu headers.

Graphics reference examples

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