OPIC LENS DESIGN TUTORIAL

Brian Blandford

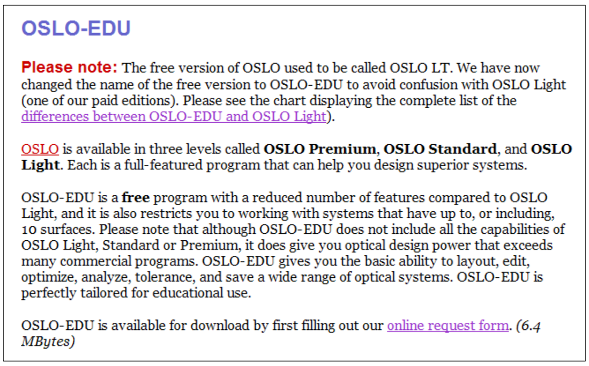
INTRODUCTION

This tutorial has been prepared for anyone who has never designed an optical instrument, nor has used an optical design program before. Its aim is to give a simple introduction for the newcomer, not only to the concepts of geometrical and physical optics, but also to the craft of lens design, and the use of any full-scale commercial optical design program.

The tutorial shows step-by-step how to download free optical software, OSLO-EDU, and use it to analyse the optical performance of a concave spherical mirror. It then demonstrates how OPIC, a software procedure in the CCL language of OSLO software, which is also available for free downloading, can be used to carry out a real design task, the design of a three-component objective.

DOWNLOADING OSLO-EDU

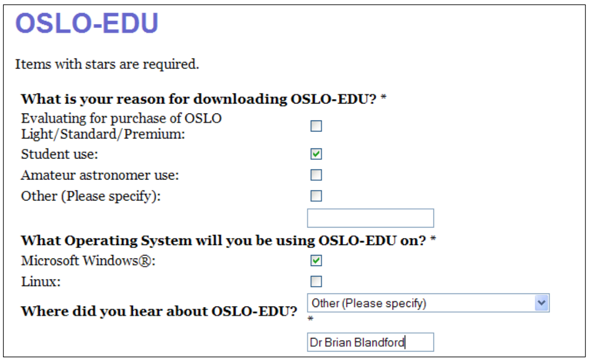
- Using an internet browser access the Lambda Research Corporation website at http://www.lambdares.com/downloads/



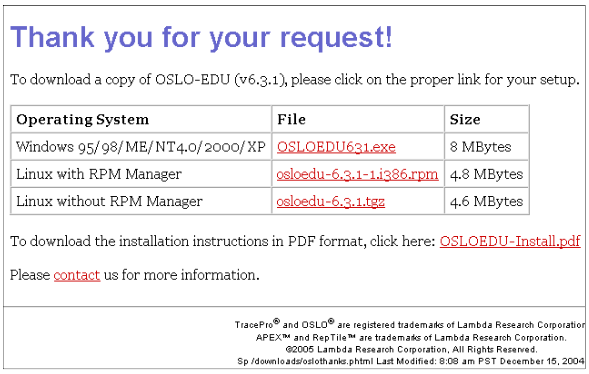
- Scroll down to the OSLO EDU paragraph shown.

- Click on the online request form.

- Fill in the form as shown. Make sure that the option "Add my e-mail to the OSLO discussion group list" is selected in the list at the end.

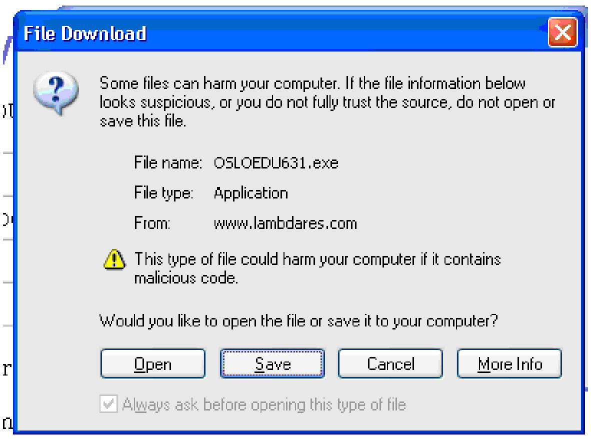


- Once you have completed the form select "Submit Query" to submit your information.



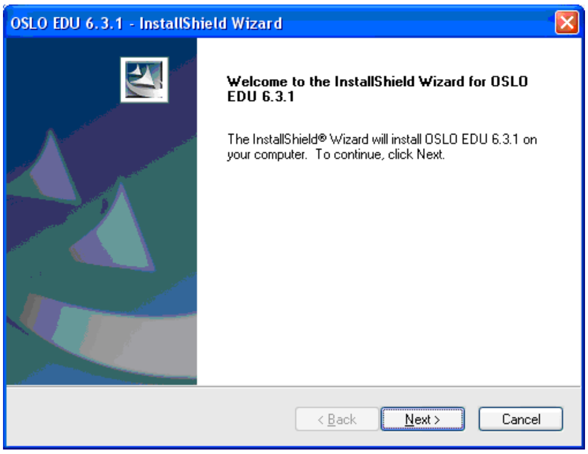
- On the following page select the appropriate download for your operating system.

- At this point you may also wish to download the accompanying installation instructions, which cover both the Windows and Linux Operating Systems. You may also download these instructions later on from the above Lambda Research link.



INSTALLING OSLO EDU IN A MICROSOFT WINDOWS ENVIRONMENT

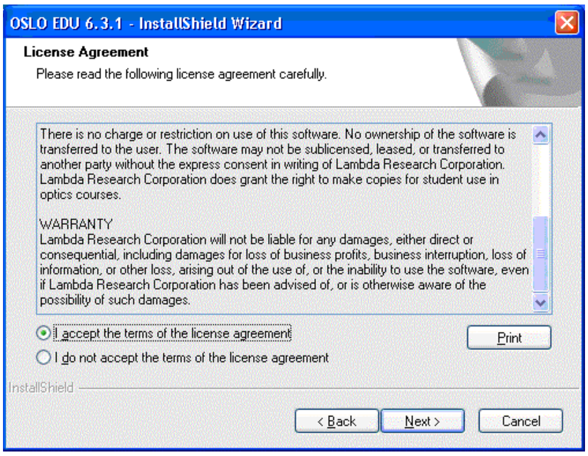
- Run the installation file you have downloaded from Lambda Research. Left-click on Next>



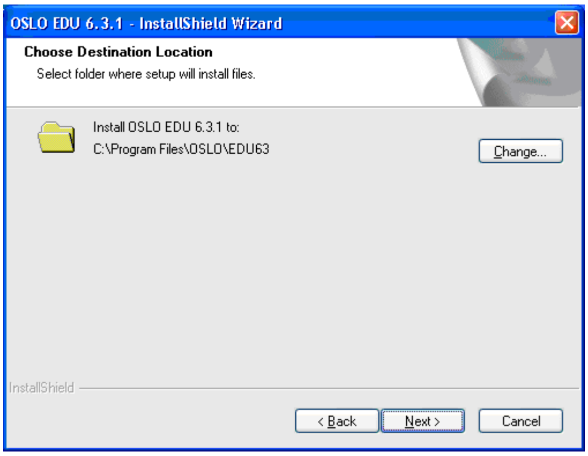
- Carefully read the License Agreement and left-click on:.

 **I accept the terms of the license agreement**

Left-click on Next>

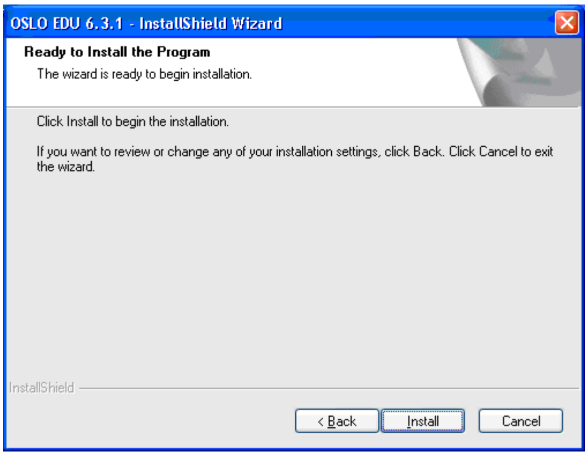


- Select an appropriate installation location. The default directory is **C:\Program Files\OSLO\EDU63** This, however, is not ideal if you do not have read-write permission to that directory. If you do not have administrator status on your computer, choose another location. Left-click on Next>

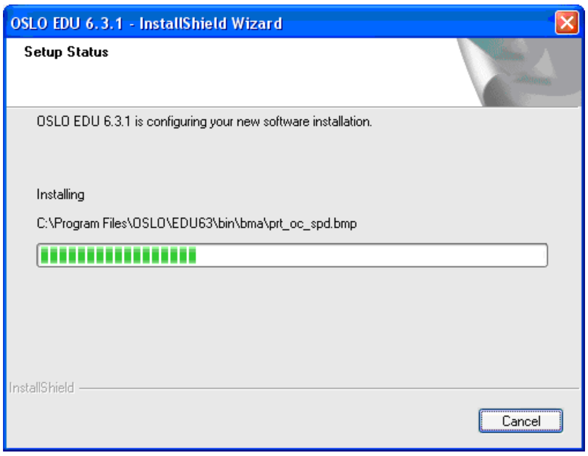


[Note to system administrator: The user requires read/write permission for all files and directories in the **C:\Program Files\OSLO\EDU63\private** *directory, particularly the* **\len** *and* **\ccl** *sub-directories]*

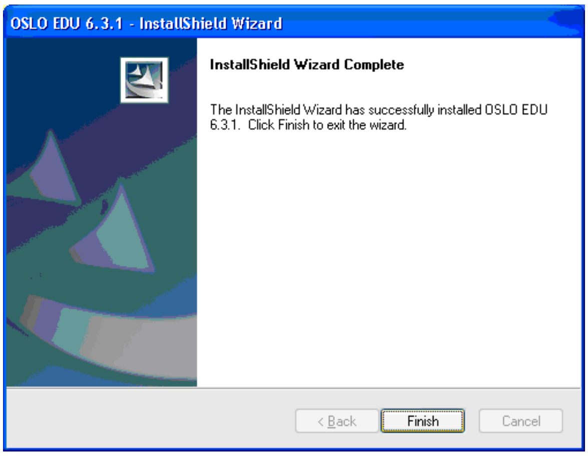
- Begin the installation. Left-click on Install>



- Wait for the program to be setup on your computer.

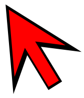
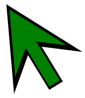


- The installation has completed successfully. Left-click on Finish.



- You may remove or modify the program installation from the "Add or Remove Programs" tool found in the Windows Control Panel.

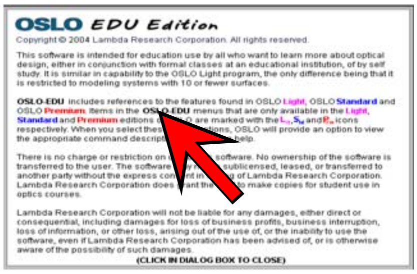
RUNNING OSLO-EDU FOR THE FIRST TIME

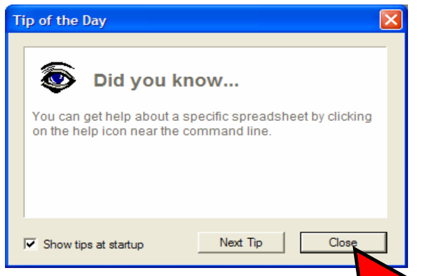
In these notes, a left click on the mouse is indicated by a red arrow, and a right click by a green arrow. Terms which are defined in the glossary at the end are in **bold**. Anything typed from the keyboard is in `this typeface`. For those with some OSLO experience, commands relevant to the current topic are shown in **this typeface.** These give examples of command syntax, and are also useful as an index to the on-line documentation, but they are not essential for a first-time reading. Notes which appear whenever the cursor hovers above an icon are shown

thus

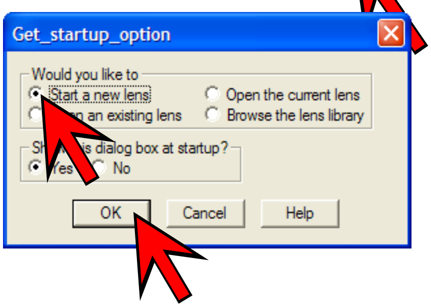
- Click on Start ► All Programs ► OSLO ► OSLO EDU Edition 6.3.1 (unless you have the desktop icon shown here)



- 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**



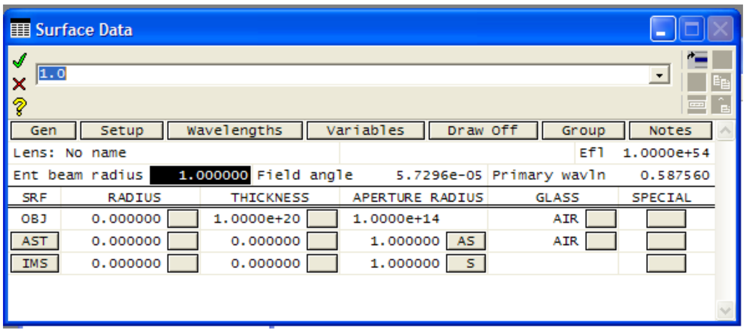
- The "tip of the day" is a useful tutorial for new users. Click on **Close**. Alternatively it can be suppressed permanently by removing the tick from the box in the bottom left corner **[stp stas on]**



- The "Get_startup_option" window opens. **[stp pstc on]** Choose the option:
  Start a new lens

  and click on **OK**

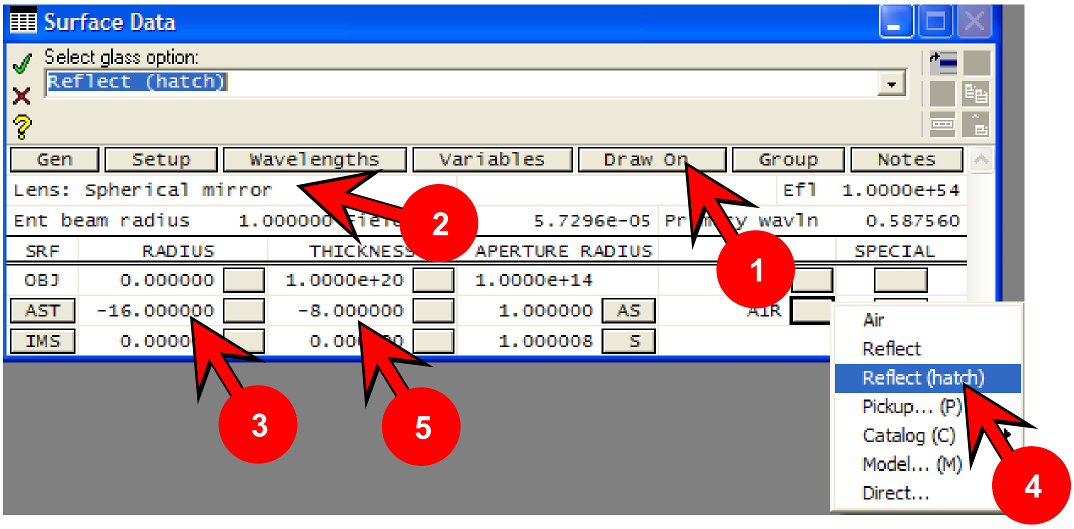
The window which opens is called the Surface Data Spreadsheet.



[lens_spreadsheet lse]

DEFINING A SPHERICAL MIRROR

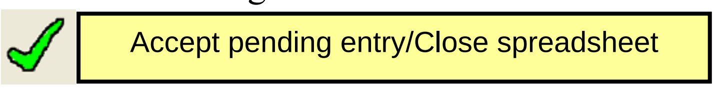
In the surface data spreadsheet:



1. Select _Draw On_ for the Autodraw window **[dlav set yz]**
2. Add the lens identifier: **Lens: `Spherical mirror.`** **[lid spherical mirror]** and click on the green tick.

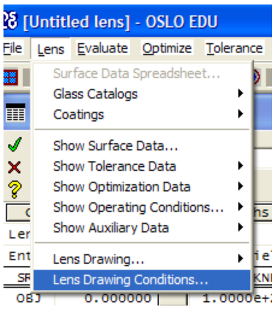
On the second line for surface 1 (**AST**):

3. Change the **RADIUS** of curvature (in mm) to: **`-16`** **[rd 1 16]**
4. Click on the grey button next to **AIR** under **GLASS** and select **Reflect (hatch)** **[gla 1 rfh]**
5. Change the **THICKNESS** - the separation to the next surface - from 0.0 to: **`-8`** (mm). **[th 1 -8]** Once again, click on the green tick to confirm the changes.



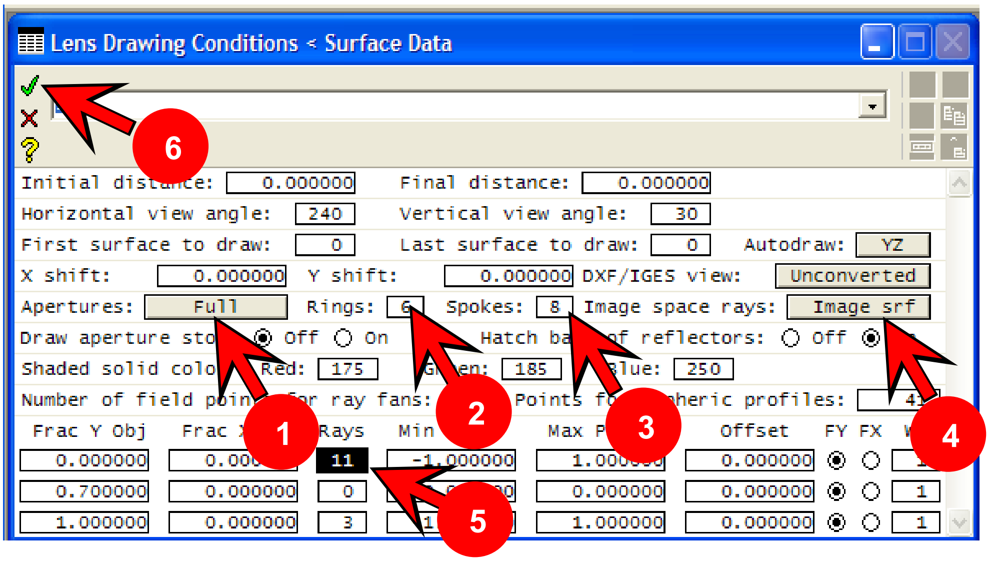
There is no need to close the Surface Data Spreadsheet, but if you do and then want to open it again, see below under "Saving the Lens".

DRAWING THE SPHERICAL MIRROR



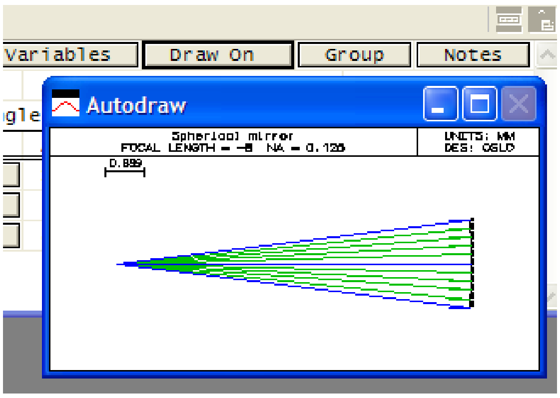
Pull down the menu from the **Lens** menu header.

Select **Lens Drawing Conditions ...**



In the lens drawing conditions spreadsheet:

1. After **Apertures:** select the option **Full apertures**. **[dlap 3]**
2. After **Rings:** type in **6** **[dlri 6]**
3. After **Spokes:** type in **8** **[dlsp 8]**
4. After **Image space rays:** select **Draw rays to image surface**.**[dlrs 3]**
5. Under the column headed **Rays** type in **11** in the first row for the number of rays to be drawn at the on axis field point (**Frac Y Obj = 0.00000**). **[dlnr 0 11]**
6. Close with the green tick:



The Autodraw window should now have the appearance shown in the diagram.

PLOTTING A SPOT DIAGRAM

Now create a map of the pattern of rays falling on the image. From the **Evaluate** menu header select:

Spot Diagram►Single spot diagram...

Click on three radio buttons:

Plot spot diagram

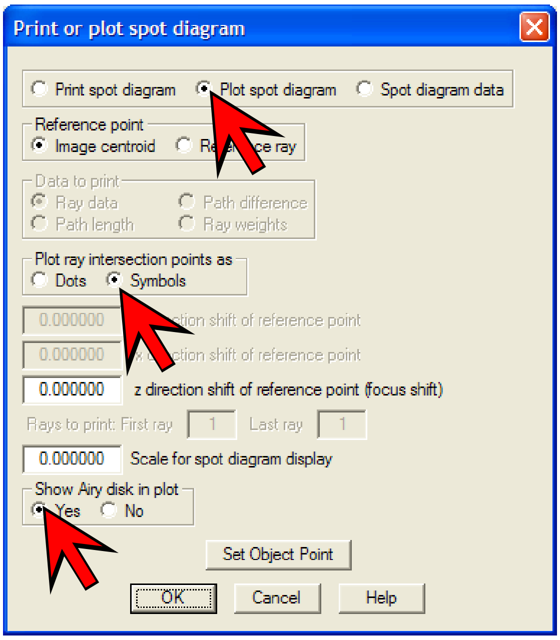
Plot ray intersection points as

Symbols

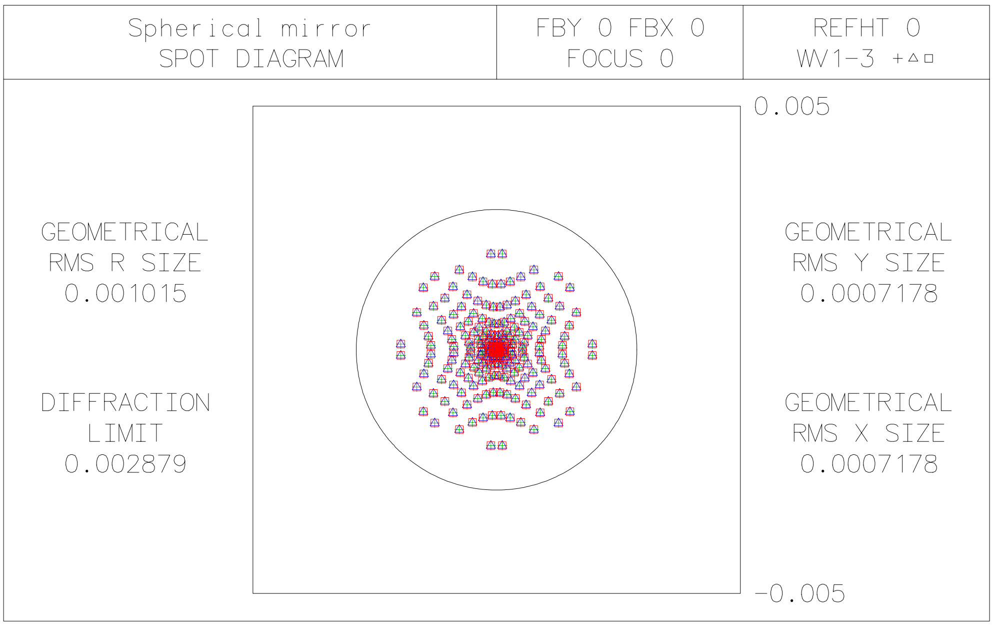
Show Airy disc in plot

Yes

Click on **OK**

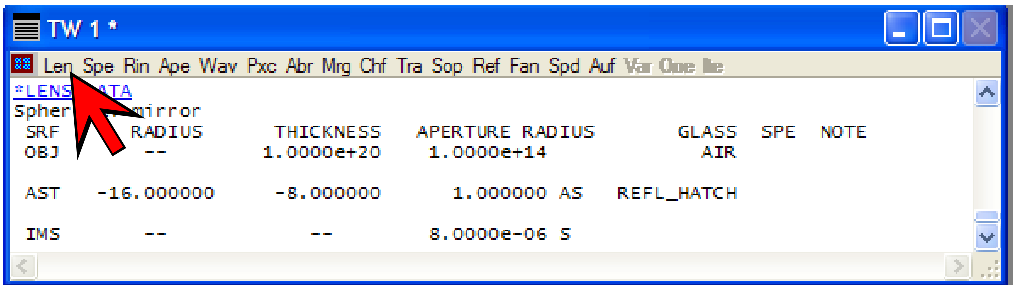


This diagram should appear. **[pls cen sym 0.0 0.0]**

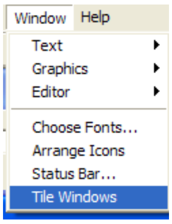


LISTING THE LENS SURFACE DATA

- List the lens data in the text window by clicking on **Len** in the text window header: **[len]**

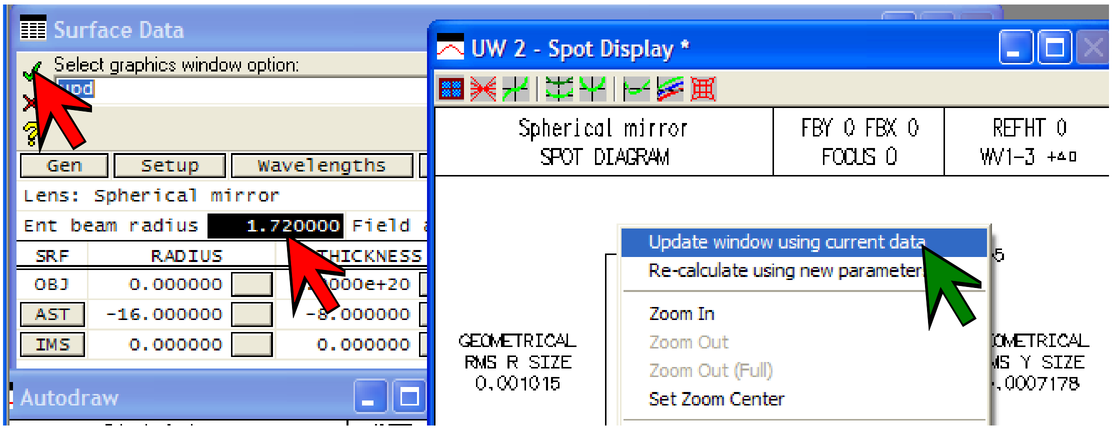


If you have trouble finding the text window, from the **Window** menu header select **Tile Windows** **[tile]**



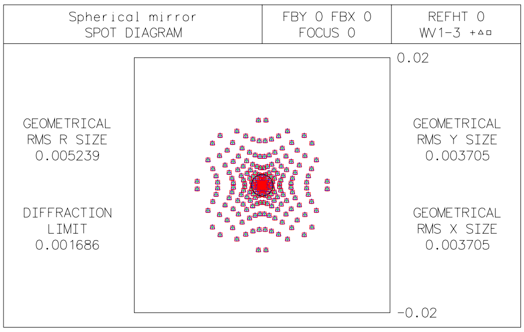
SEEING THE EFFECT OF INCREASED APERTURE

- In the surface data spreadsheet increase the entrance beam radius from 1 mm to **1.72** mm as shown in the diagram below. **[ebr 1.72]**
- Confirm with the green tick. 
- Recalculate the spot diagram by right-clicking inside the window and selecting **Update window using current data:**

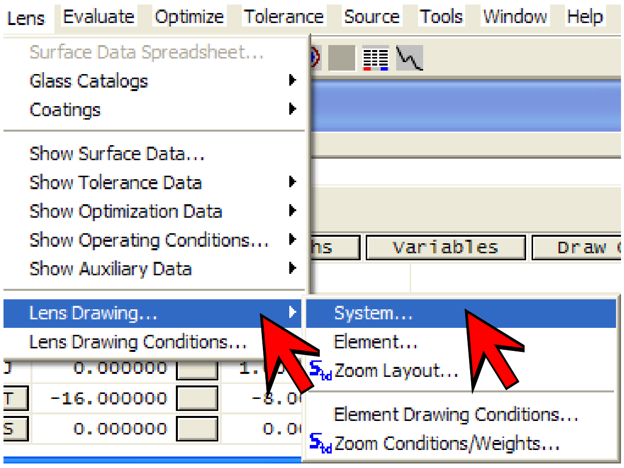


to give the diagram shown.

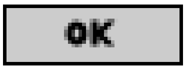
The spot diagram is now bigger, and the Airy disc is smaller, than before.



CHOOSING A BETTER FOCAL PLANE

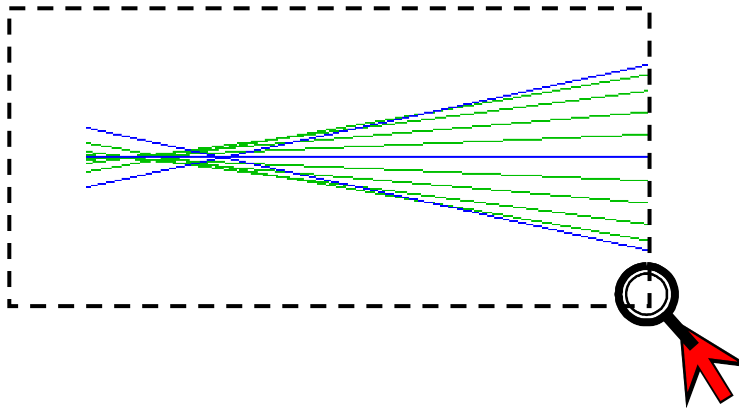


Draw the lens system in a graphics window:

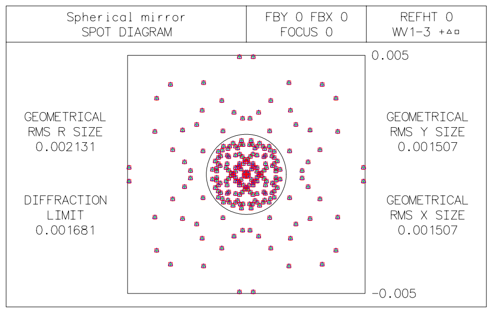
- From the **Lens** menu header select **Lens Drawing ...** ► **System**
- Accepting all the defaults click on 

[drl; drr fby y 0 11 -1.0 1.0 0 0]

- On the graphics window, left-click-and-drag around the focus to view the pattern of rays at higher magnification - this is called “zooming”. (Note - there is a limit to the extent you can zoom in - open up the window to see the full magnification).



- Double click (left) on the graphics window to zoom out to the full screen view (you cannot do these zoom actions in the Autodraw window).



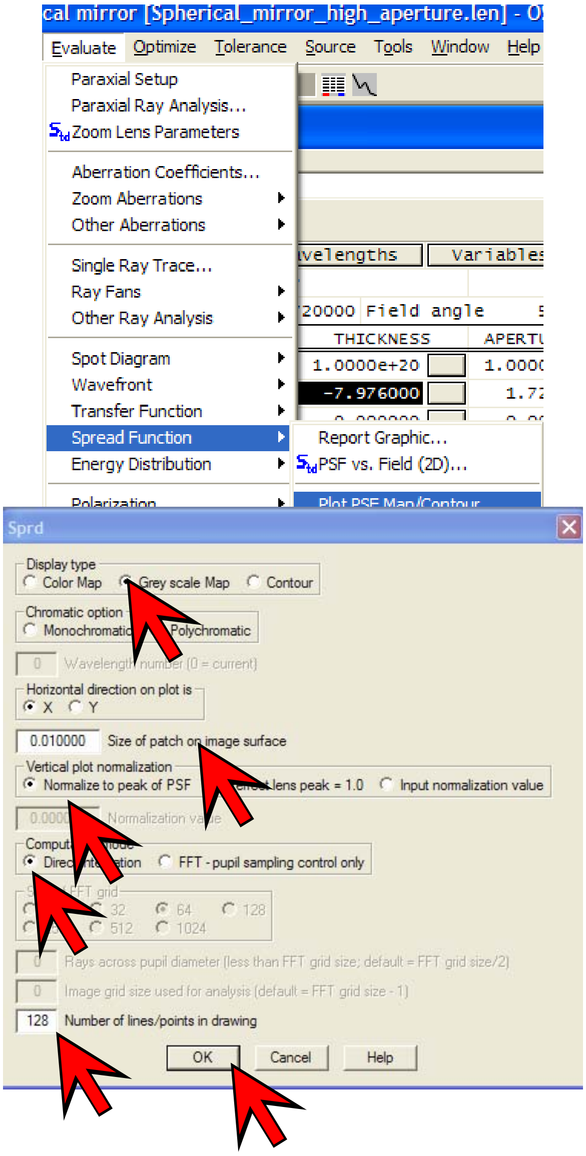
Clearly a better focal plane can be chosen, a short distance to the right of the current one. You might like to experiment to find the one which gives the smallest spot. Otherwise, try this value:

- Change the thickness at surface 1 from -8.00 mm to **-7.976** mm.
- From the **Evaluate** menu header select **Spot Diagram** ► **Single spot diagram...** and choose the same options as before.

PLOTTING THE POINT SPREAD FUNCTION

Plot the distribution of light at the focus - the point spread function.

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



In the window which opens:

- Click on the radio button:
  ◉ **Grey scale map**

- Type in **0.01** for the
  Size of patch on image surface.

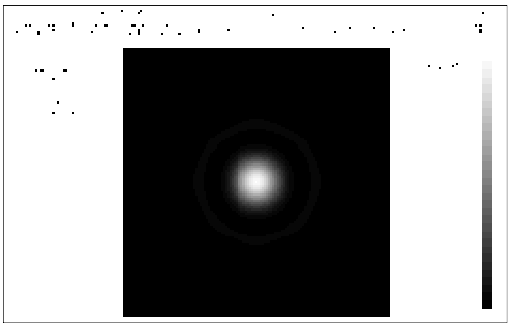
- Click on the radio button:
  ◉ **Normalize to peak of PSF**

- Click on the radio button:
  ◉ **Direct integration**

- Type in **128** for
  Number of lines/points in drawing

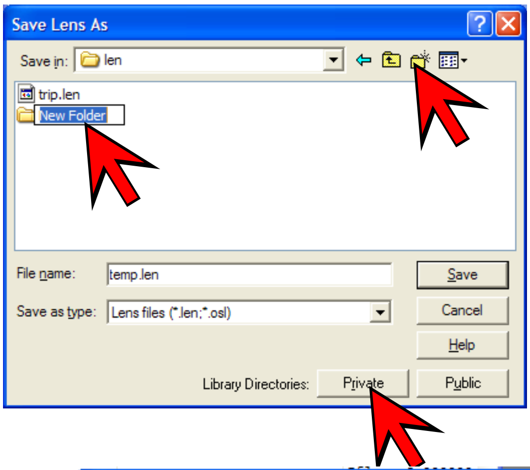
and click on **OK**.

[sprd gry chr x 0.0 pek dir 128]



Close inspection shows that the central peak is surrounded by at least one light ring which is just visible. Note the figure at the top of the scale on the right - **0.788**. This figure is called the Strehl ratio. A figure of 0.8 or above is very good for most applications.

SAVING THE LENS

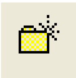


Save the lens in a new folder.

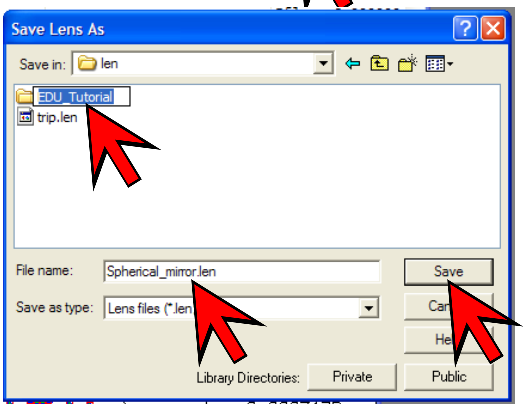
- From the **File** menu header select **Save Lens as ...**

- Click on **_Private_**

- Click on:



Create new folder



- Type the name for the new folder: **`EDU_Tutorial`** and click on **_Open_**

- Save the lens with the name: **`Spherical_mirror.len`** by clicking on **_Save_**.

- Close the surface data spreadsheet with the green tick:

Accept pending entry/Close spreadsheet

The surface data spreadsheet may be re-opened: Either, from the **Lens** menu header select **Surface Data Spreadsheet...** or click on the blue lens icon in the main screen toolbar. **[lse]**

[shp prid = show_preference Private_directory]
[shp lfil = show_preference Lens_file]
[save len pri "len" "EDU_Tutorial/Spherical_mirror"]

EXITING THE PROGRAM

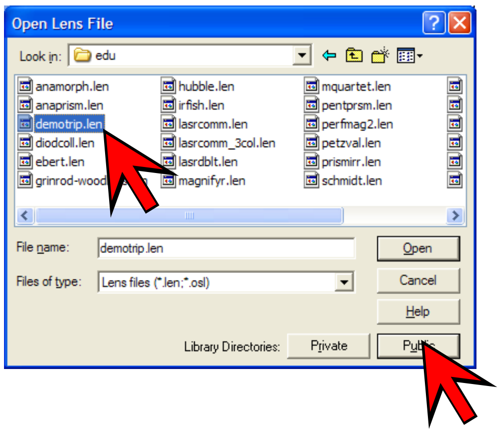
From the **File** menu header select **Exit** **[exit]**

OPTIMISATION USING OPIC

INTRODUCTION

Note: The first part of this tutorial is essentially copied from the document "Optimization Tutorial using OSLO Light," which is available as a free PDF download from the Lambda Research Corporation web site at the following URL:
http://www.lambdares.com/techsupport/tutorials.phtml
It is recommended that the section "Lens Entry" is followed using both documents in parallel. The steps numbered 1 to 16 below correspond to steps 1 - 16 in the tutorial.

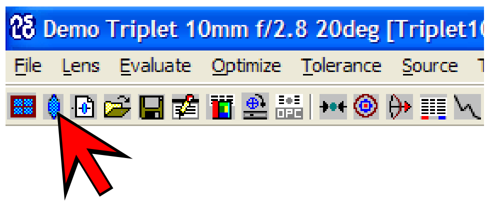
The customer requirement may be summarised as follows: A triplet objective is required, of focal length 10 millimetres, and a field of view of 40° (± 20°), which will have an aperture ratio of f/2.8. Vignetting is permitted, with up to 50% brightness reduction at the extreme field of view. The MTF must be greater than 0.4 at 40 lines/mm everywhere in the field. Distortion must be less than 1%.



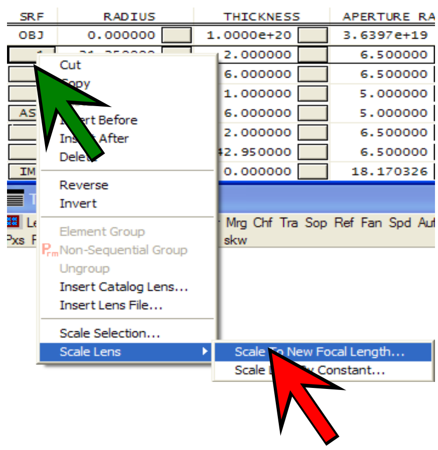
LENS ENTRY

1. Open the lens in the public directory:
   C:ProgramFiles\OSLO\EDU63\public\len\demo\edu
   with the file name **demotrip.len**

   Save it in the private directory: **C:ProgramFiles\OSLO\EDU63\private\len\EDU_Tutorial** with the same file name.



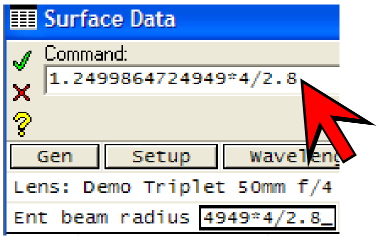
2. If it is not open already, open the surface data spreadsheet by clicking on the blue lens icon in the main window toolbar.**[lse]**



3. Scale the lens to focal length 10 mm by right-clicking on any surface number button, and selecting **Scale Lens** ►**Scale to**

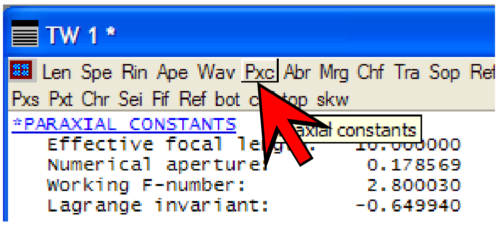
New Focal Length ► **Enter scaled focal length: `10.0`. [sle to 10.0]**

4. Change the entrance beam radius from its current value giving an f-number of f/4 to give an f-number of f/2.8 **[ebr 1.785710]**

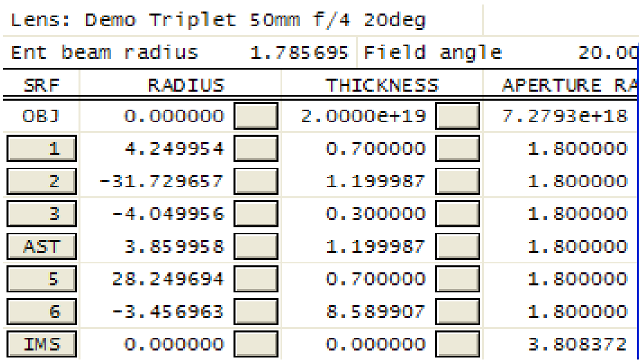


5. Verify the f-number using the text window header **Pxc. [pxc]**

6. Increase the aperture radii of surfaces 1 to 6 to 1.8 **[ap 1 1.8] [ap 2 1.8].. [ap 6 1.8]**



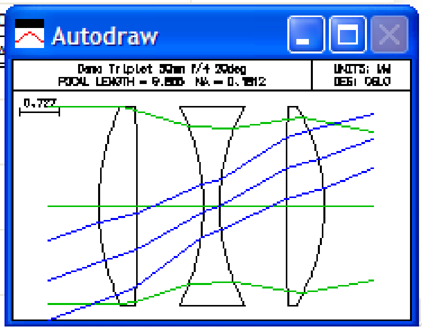
7. Increase the thickness of the first element to 0.7 mm, of the second element to 0.3 mm, and of the third element to 0.7 mm. **[th 1 0.7]**, **[th 3 0.3]**, **[th 5 0.7]**



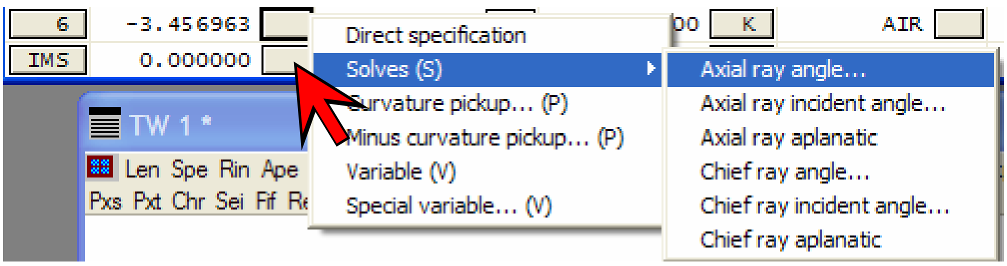
Lens: Demo Triplet 50mm f/4 20deg — Efl 9.854505

Ent beam radius 1.785695 Field angle 20.00

SRF	RADIUS	THICKNESS	APERTURE RA
OBJ	0.000000	2.0000e+19	7.2793e+18
1	4.249954	0.700000	1.800000
2	-31.729657	1.199987	1.800000
3	-4.049956	0.300000	1.800000
AST	3.859958	1.199987	1.800000
5	28.249694	0.700000	1.800000
6	-3.456963	8.589907	1.800000
IMS	0.000000	0.000000	3.808372

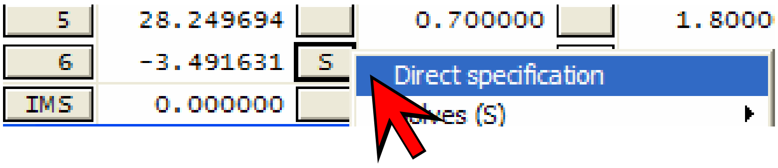


8. Adjust the radius of surface 6 to restore the focal length to 10 mm using the following method:



Right-click on the grey RADIUS button for surface number 6, and select **Solves(S)** ► **Axial ray angle ...** ► **Enter solve value:** **`-0.1785695`** (this is -0.1 times the entrance beam radius)

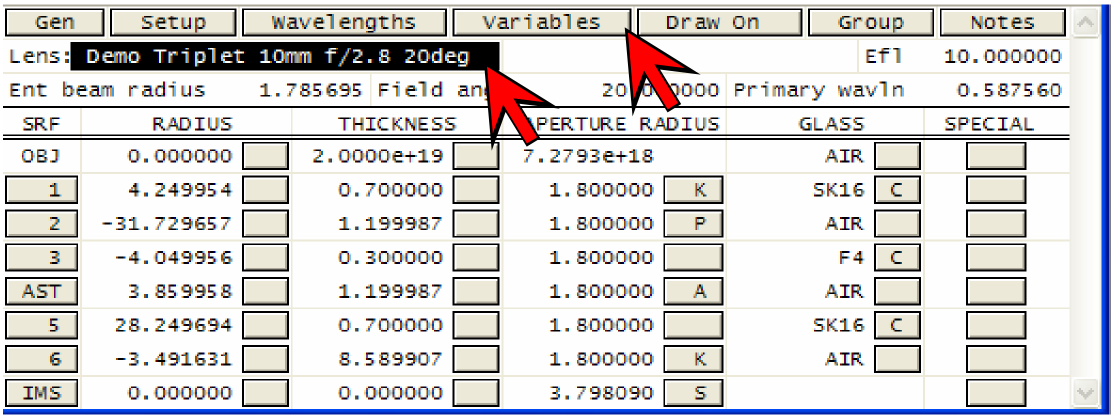
9. Remove the curvature solve on surface 6: Click on the grey RADIUS button for surface 6, and select **Direct specification**. The "S" should vanish.



[pu -0.1785695;csd 6 or **rd 6 -3.491631]**

10. Verify the effective focal length is 10mm.

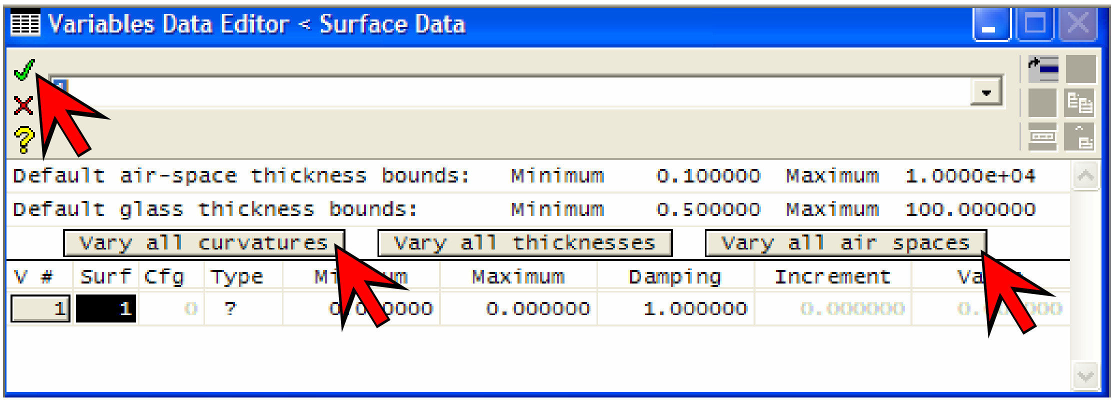
11. Change the title to **Demo Triplet 10 mm f/2.8 20deg**.



SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		2.0000e+19		7.2793e+18		AIR		
1	4.249954		0.700000		1.800000	K	SK16	C	
2	-31.729657		1.199987		1.800000	P	AIR		
3	-4.049956		0.300000		1.800000		F4	C	
AST	3.859958		1.199987		1.800000	A	AIR		
5	28.249694		0.700000		1.800000		SK16	C	
6	-3.491631		8.589907		1.800000	K	AIR		
IMS	0.000000		0.000000		3.798090	S			

Save the lens as **Triplet10mm_Start.len** in the directory **C:ProgramFiles\OSLO\EDU63\private\len\EDU_Tutorial.**

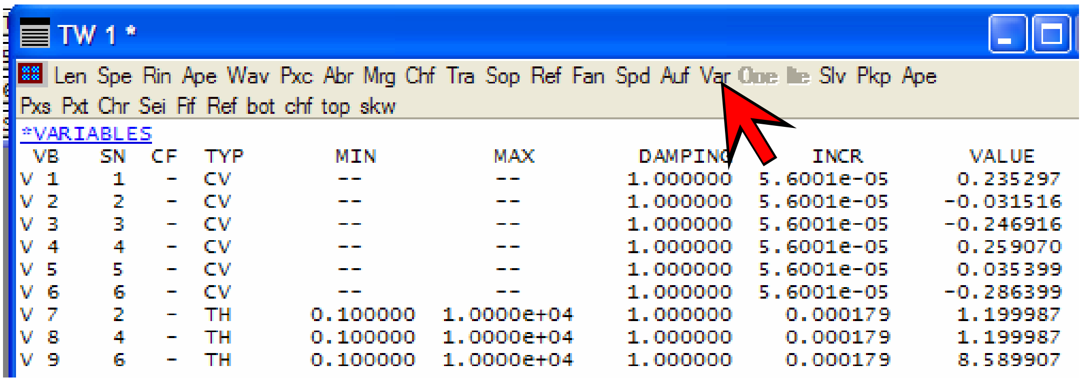
12. Open the variables data editor: click on the button labelled **Variables** in the lens data editor. **[vse]**



13. Click on **Vary all curvatures.** Click on **Vary all air spaces.**

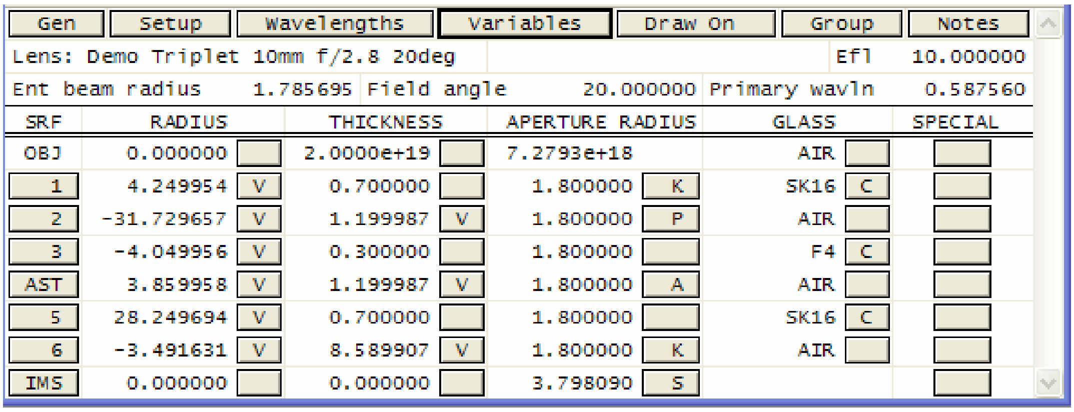
14. Close the variables spreadsheet with the green tick:

15. Using the text window header **Var**, check that there are now 9 variables. **[var]**



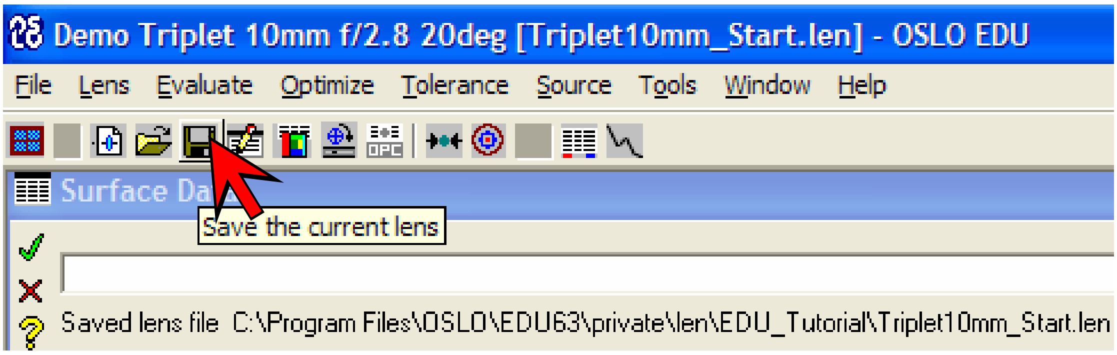
VB	SN	CF	TYP	MIN	MAX	DAMPING	INCR	VALUE
V 1	1	-	CV	--	--	1.000000	5.6001e-05	0.235297
V 2	2	-	CV	--	--	1.000000	5.6001e-05	-0.031516
V 3	3	-	CV	--	--	1.000000	5.6001e-05	-0.246916
V 4	4	-	CV	--	--	1.000000	5.6001e-05	0.259070
V 5	5	-	CV	--	--	1.000000	5.6001e-05	0.035399
V 6	6	-	CV	--	--	1.000000	5.6001e-05	-0.286399
V 7	2	-	TH	0.100000	1.0000e+04	1.000000	0.000179	1.199987
V 8	4	-	TH	0.100000	1.0000e+04	1.000000	0.000179	1.199987
V 9	6	-	TH	0.100000	1.0000e+04	1.000000	0.000179	8.589907

The lens data spread sheet should have the following appearance:



SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		2.0000e+19		7.2793e+18		AIR		
1	4.249954	V	0.700000		1.800000	K	SK16	C	
2	-31.729657	V	1.199987	V	1.800000	P	AIR		
3	-4.049956	V	0.300000		1.800000		F4	C	
AST	3.859958	V	1.199987	V	1.800000	A	AIR		
5	28.249694	V	0.700000		1.800000		SK16	C	
6	-3.491631	V	8.589907	V	1.800000	K	AIR		
IMS	0.000000		0.000000		3.798090	S			

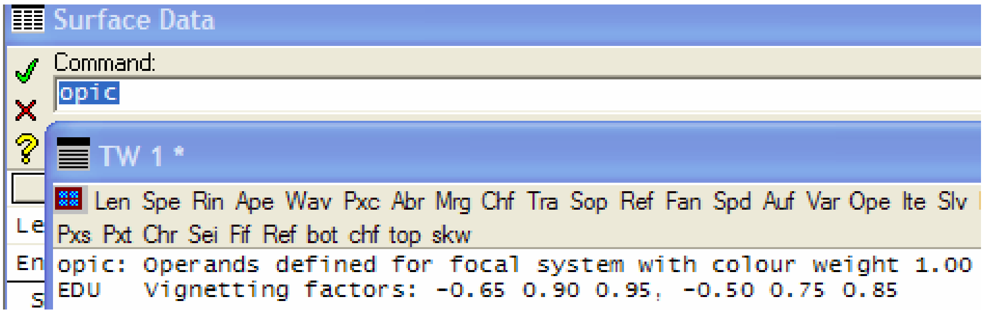
16. Save the lens again. **[save]**



This completes the section duplicated in the document "Optimization Tutorial using OSLO Light." The section which follows may be regarded as being a sequel to the two sections "Optimization using the Aberration Error Function" and "Optimization using the GENII Error Function" in that document.

OPTIMISATION USING THE OPIC ERROR FUNCTION

17. Type the command **opic** in the command line. If the error message **Input error: Unrecognized word 'opic'** appears, the command has not been installed and compiled - see Appendix 1.



Note the message in the text window. The "Vignetting factors" on the second line are the (relative) values of **ymin, ymax** and **xmax** for the two off-axis points, at (relative) field heights of 0.7 and 1.0 respectively. These figures are used in the lens drawing conditions spreadsheet (see below).

The procedure above applies to those running OPIC-EDU version within OSLO EDU. An alternative version is available for those with access to OSLO Standard or OSLO Premium. This includes several versions of OPIC, including the one described here. In this case the appropriate command is **opicedu**.

18. Optimise ("iterate") 10 times by clicking on the text window header **Ite** once **[ite]** No further improvement is necessary.

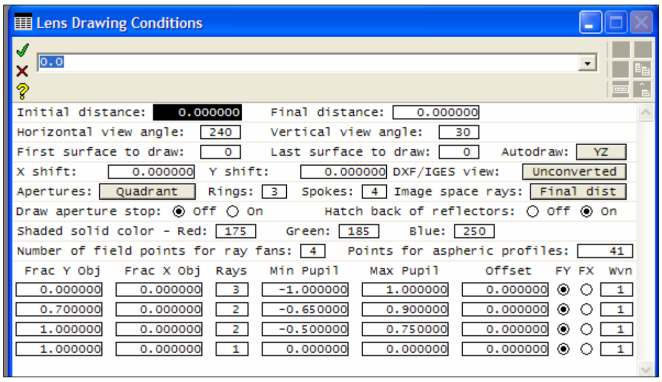
19. Save as **Triplet10mm_opicedu.len** in the same directory as the starting lens: **C:ProgramFiles\OSLO\Edu63\private\len\EDU_Tutorial\.**

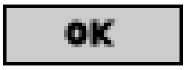
DRAWING THE FINAL DESIGN

20. Pull down the menu from the **Lens** menu header and select **Lens Drawing Conditions ...**. **[uoc drl]** In the lens drawing conditions spreadsheet:
    - After **Number of field points for ray fans:** enter **4**.
    - Under the column **Frac Y Obj** type **1.0** in the fourth row.
    - Under the column **Rays** type **2** in the second row, **2** in the third row and **1** in the fourth row.

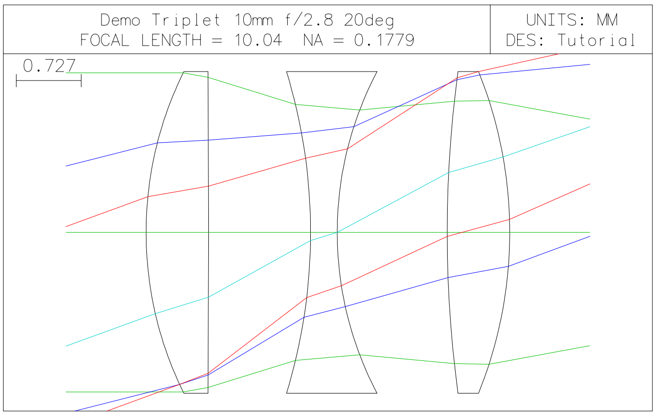
- Under the column **Min Pupil,** type **-0.65** in the second row, **-0.5** in the third row. These are the values of **ymin** for object heights 0.7 and 1 generated by the call of **opic** described in section 17 above).
- Under the column **Max Pupil,** type in the **ymax** values, **0.9** in the second row, **0.75** in the third row.
- Close with the green tick: 

21. Draw the lens:



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

Note the ray colour sequence is green, blue, red, light blue.



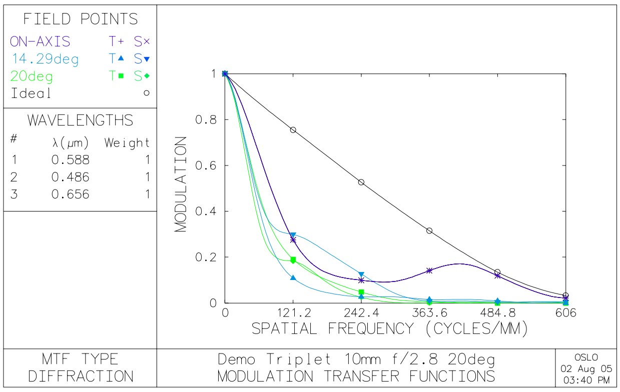
EVALUATING THE FINAL DESIGN

MODULATION TRANSFER FUNCTION

22. Calculate the cut-off spatial frequency at the image using the formula:

Maximum frequency = 2 * numerical aperture/wavelength

Use the central (first) wavelength in this calculation (click on the text window header **Pxc** to find the image space numerical aperture, and on the header **Wav** to find the wavelength in microns). The



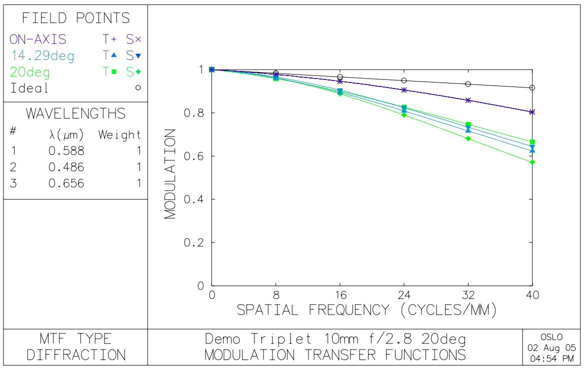
answer should be 606 cycles per mm.

23. From the **Evaluate** menu header select **Transfer function ► Through frequency report graphic ...** and enter the figure calculated (**606.0**) in the box labelled **Maximum frequency**.

Click on **OK**

This gives a plot of the MTF out to the diffraction limit (the MTF at the limit is not quite zero as there are three wavelengths, and only the central one was used for the calculation). **[rpt_tfr 606.0]**

24. Plot the same diagram out to a frequency of only 40 cycles/mm. Note that the MTF is above 0.5 (all curves) at 40 cycles/mm. **[rpt_tfr 40.0]**



VIGNETTING

25. To define the object point at full field, in the command window type: **sop 1.0 0.0 0.0**

26. To calculate the amount of vignetting at this field point, in the command window type **spd**

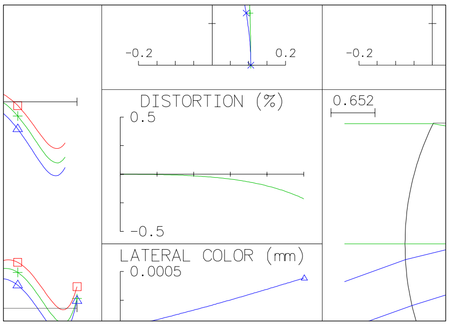
```
*SET OBJECT POINT
         FBY          FBX          FBZ
      1.000000        --           --
        FYRF         FXRF          FY           FX
         --           --           --           --
   YC          XC          YFS          XFS          OPL     REF SPH RAD
 3.606943      --        -0.056343    -0.013109    13.420286    11.823588

*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
       136          136          136
 PER CENT WEIGHTED RAY TRANSMISSION:     58.620690

*SPOT SIZES
 GEO RMS Y    GEO RMS X    GEO RMS R   DIFFR LIMIT     CENTY        CENTX
  0.002980     0.003971     0.004964     0.002303    -0.000570       --

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD      RMS OPD   STREHL RATIO     RSY          RSX          RSZ
    1.025286     0.250318     0.180992    -0.000850       --           --
```

27. Note the “Per cent weighted ray transmission” value. The brightness reduction is only 41% at the extreme edge of the field.

DISTORTION

28. From the **Evaluate** menu header select **Other ray analysis** ►**Report graphic ...** and accept all the defaults.

29. Note that the distortion is less than 0.3% everywhere in the field. **[rpt_ric ray 0 0 0]**



It may be concluded that the nominal design of this lens meets all the requirements of the customer specification by some margin. For the next stage of the design, the calculation of tolerances, this margin is used in the calculation, so that the lenses delivered in production all meet the customer requirement.

As a final check, the prescription of this lens is listed below using **Len** and **Pxc** in the text window:

```
*LENS DATA
Demo Triplet 10mm f/2.8 20deg
 SRF       RADIUS        THICKNESS   APERTURE RADIUS       GLASS  SPE
NOTE
 OBJ         --         2.0000e+19    7.2793e+18             AIR

  1      4.052520 V     0.700000      1.800000 K            SK16 C
  2   -228.402737 V     1.141096 V    1.800000 P             AIR

  3     -6.145935 V     0.300000      1.800000                F4 C
 AST     3.857846 V     1.231107 V    1.800000 A             AIR

  5     13.439422 V     0.700000      1.800000              SK16 C
  6     -4.807852 V     7.824421 V    1.800000 K             AIR

 IMS         --            --         3.633524 S

*PARAXIAL CONSTANTS
Effective focal length: 10.035628 Lateral magnification:  -5.0179e-19
Numerical aperture:       0.177937 Gaussian image height:     3.652670
Working F-number:         2.809983 Petzval radius:          -23.067815
Lagrange invariant:      -0.649945
```

APPENDICES

1. DOWNLOADING AND COMPILING OPIC

- Using an internet browser, open the knowledge base page of the Lambda Research Corp website **(Home>Tech Support>Knowledge Base),** URL http://www.lambdares.com/techsupport/kb/index.phtml
- Left click on **OPIC (CCL file)**
- In the page which opens, under the header, left click on **Click to begin the download**
- The file will have name **optim_ic_EDU.ccl**. Left click on **Save.**
- In the **Save in:** area at the top, navigate to the directory **C:ProgramFiles\OSLO\EDU63\private\ccl** The file type should be **OSLO CCL File.** Left click on **Save**. *[Take care: Store the file in the Private CCL directory, not in a subdirectory. The file extension must remain .ccl]*
- Close the internet browser and open OSLO EDU.
- Either, in the command window, type: **`ccl`**, or, from the menu header **Tools** select **Compile CCL ...** and click on the green tick three times, accepting the default each time.
- If the message in the text window reads: ***CCL COMPILATION MESSAGES:** **No errors detected** then compilation is successful.
- If error messages appear in the text window such as:

***CCL COMPILATION MESSAGES:**
optim_ic_edu.ccl 8: Name 'colour_weight' has already been declared
optim_ic_edu.ccl 133: Duplicate procedure definition
optim_ic_edu.ccl 385: Duplicate procedure definition

then the opic command appears in a file already stored in this directory. The old file needs to be either deleted, or have its name changed to (for example) **optim_ic_edu_old.ccx** (The **.ccx** extension is a signal that the file is not to be compiled).

- If any editing is needed, from the menu header, select **Window** ► **Editor** ► **Open** and open **optim_ic_EDU.ccl**. If you save from this editor, compilation takes place automatically.
- Open any lens, and in the command window, type: **`opic`**. A message like the following should appear in the text window to indicate that all is working well:

opic: Operands defined for focal system with colour weight 1.00
EDU Vignetting factors ymin ymax xmax ymin ymax xmax
for FBY = 0.7, 1.0: -0.60 0.80 0.95, -0.40 0.60 0.80

If OPIC EDU is run within OSLO Standard or OSLO Premium, use the command **`opicedu`** *instead of* **`opic`** *to avoid conflict with another command of the same name, stored in the file Take care*

2. OPIC DOCUMENTATION

The following documentation is contained within the **optim_ic_EDU.ccl** file:

OPIC for OSLO EDU

Contributed by Brian Blandford
Email: brian.blandford@physics.org

Generates an error function based on those developed in the 1970s at Imperial College, London by Charles Wynne,Pru Wormell,Mike Kidger and others. This version is intended primarily for users of OSLO LT, OSLO EDU or OSLO Light, but will work with all versions of OSLO.

The command calculates vignetting, and then defines an optimisation error function with 50 operands.

The optimisation error function consists of the weighted sum of the following operands:

Four paraxial ray quantities:

1 **PY** Height of the paraxial axial marginal ray at the image
2 **PU** Angle of this ray in the image space
3 **PYC** Height of the paraxial pupil (chief) ray at the image
4 **PUC** Angle of this ray in the image space

Two first order chromatic coefficients for wavelengths 2 and 3:

5 **PAC** Primary axial (longitudinal) chromatic focal shift
6 **PLC** Primary lateral chromatic aberration

Two first order chromatic coefficients for wavelengths 1 and 2:

7 **SAC** Secondary axial (longitudinal) chromatic focal shift
8 **SLC** Secondary lateral chromatic aberration

Two geometrical optics parameters:

9 **OALL** The overall lens length (from srf 1 to srf IMS-1)
10 For focal systems, the equivalent focal length **EFL**;
for afocal systems, the paraxial angular magnification **AMAG**.

A user-defined operand:

11 **User**: A spare parameter for user-defined operands programmed by the user within **optim_ic_EDU.ccl**. The routine is supplied with the mean RMS spot radius for the field points FBY = 0.0, 0.7, 1.0 as an example.

The remaining aberrations are those of finite rays:

For focal systems, all monochromatic ray aberrations are linear - (DX, DY etc). For afocal systems they are angular (DXA, DYA etc) expressed as direction tangents - e.g YA=L/M or tan(YANG).

Colour aberrations (COL) are optical path differences between wavelengths 2 and 3, known as the "Conrady D minus d" - or DMD - see Welford WT: Aberrations of Optical Systems (Adam Hilger 1986) p 202.

For the axial object point (FBY = 0):

12 **A_DY** the aberration of the marginal ray FY = 1.0).
13 **A_COL** The chromatic optical path difference of this ray
14 **A_Z_DY**For the axial object point, the zonal ray (FY = 0.7)
15 **A_Z_COL** The chromatic optical path difference of this ray

For the first off-axis image point (FBY = 0.7):

16 **M_XFS** The paraxial sagittal focal shift of the pupil ray.
17 **M_YFS** The paraxial tangential focal shift of the pupil ray.
18 **M_DIST%** The percentage distortion at the 0.7 field
19 **M_T_DY** The aberration of the top marginal ray (FY = +1.0)
20 **M_T_COL** The chromatic optical path difference of this ray
21 **M_TZ_DY** The aberration of the top zonal ray (FY = +0.7)
22 **M_TZ_COL** The chromatic optical path difference of this ray
23 **M_BZ_DY** The aberration of the bottom zonal ray (FY = -0.7)
24 **M_BZ_COL** The chromatic optical path difference of this ray
25 **M_B_DY** The aberration of the bottom marginal ray (FY = -1.0)
26 **M_B_COL** The chromatic optical path difference of this ray
27 **M_S_DX**The aberration of the sagittal marginal ray (FX = +1.0)
28 **M_S_DY** The aberration of this ray in the Y direction
29 **M_S_COL** The chromatic optical path difference of this ray
30 **M_SZ_DX** The aberration of the sagittal zonal ray (FX = +0.7)
31 **M_SZ_DY** The aberration of this ray in the Y direction
32 **M_SZ_COL** The chromatic optical path difference of this ray

For the second off-axis image point (FBY = 1.0)

33 **E_XFS** The paraxial sagittal focal shift of the pupil ray.
34 **E_YFS** The paraxial tangential focal shift of the pupil ray.
35 **E_DIST%** The percentage distortion at the edge of the field
36 **E_PLC**The lateral primary chromatic aberration of the pupil ray
37 **E_T_DY** The aberration of the top marginal ray (FY = +1.0)
38 **E_T_COL** The chromatic optical path difference of this ray
39 **E_TZ_DY** The aberration of the top zonal ray (FY = +0.7)
40 **E_TZ_COL** The chromatic optical path difference of this ray
41 **E_BZ_DY** The aberration of the bottom zonal ray (FY = -0.7)
42 **E_BZ_COL** The chromatic optical path difference of this ray
43 **E_B_DY** The aberration of the bottom marginal ray (FY = -1.0)
44 **E_B_COL** The chromatic optical path difference of this ray
45 **E_S_DX** The aberration of the sagittal marginal ray (FX = +1.0)
46 **E_S_DY** The aberration of this ray in the Y direction
47 **E_S_COL** The chromatic optical path difference of this ray
48 **E_SZ_DX** The aberration of the sagittal zonal ray (FX = +0.7)
49 **E_SZ_DY** The aberration of this ray in the Y direction
50 **E_SZ_COL** The chromatic optical path difference of this ray

To use:

1. Type in command: **opc gen** [operating_conditions general]
Check that the evaluation mode (focal/afocal) of the starting design is correct.

2. Type in command: **pxs** [paraxial_setup]

Check that the starting design has the desired values of the key parameters for the four types of optical system:

Objective (infinite-finite, focal)
the effective focal length and entrance beam radius
Reverse objective (finite-infinite, afocal)
the effective focal length and object numerical aperture
Relay (finite-finite, focal)
the paraxial magnification and object numerical aperture
Telescope (infinite-infinite, afocal)
the paraxial angular magnification and entrance beam radius

3. Type in command **rpt_ric ray 0 0 0**[ray intercept report graphic]
Check that at least part of the pupil is traced for each of the three default field points (axis, 0.7 and full field).

4. Then call by typing the command **opic** (or e.g. **opic 0.5** - the number scales the relative weights of all chromatic ray aberrations; the default value for colour_weight is 1.0)

5. For focal systems:
Check that the target on operand 2 is the target numerical aperture (**PU**) required, and that the target on operand 9 is the target overall
lens length (**OALL**).
If equivalent focal length (**EFL**) is to be controlled, check that the target for operand 10 is the value required and assign a weight.
For afocal systems:
Check that the target on operand 1 is the paraxial marginal ray height (**PY**) for the desired magnification. Also check that the target on operand 9 is the desired overall lens length (**OALL**).
If angular magnification is to be controlled, check that the target for operand 10 is the value (**AMAG**) required, and assign a weight.

6. Define some variable parameters (command **vse**) such as curvatures.

7. Type in command **ite** (or click on Ite in the text window header.

Exceptions:

The mid-field distortion value is incorrect for ray aiming mode = "wide angle". If the aperture is expressed as image space NA or controlled by an angle solve on the last curve, the **PU** control will not be effective - weight the **EFL** instead.