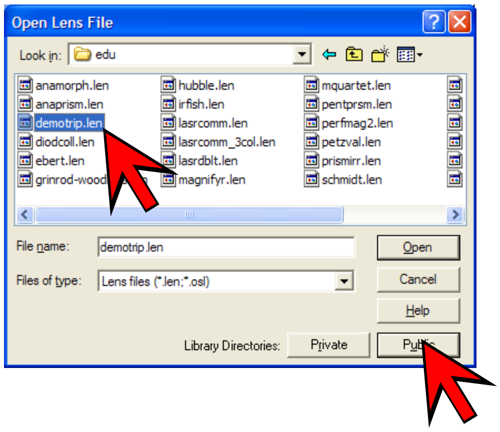
11. OPTIMISATION USING OPIC

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/technical_support/oslo/tutorials/
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.

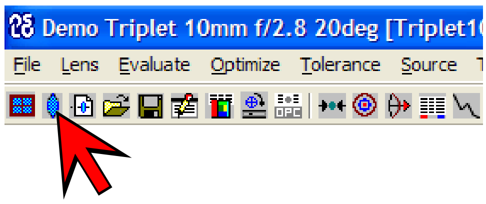
The customer requirement may be summarised as follows: A triplet objective is required, of focal length 10 millimetres, and a field of view of 40° (± 20°), which will have an aperture ratio of f/2.8. Vignetting is permitted, with up to 50% brightness reduction at the extreme field of view. The MTF must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



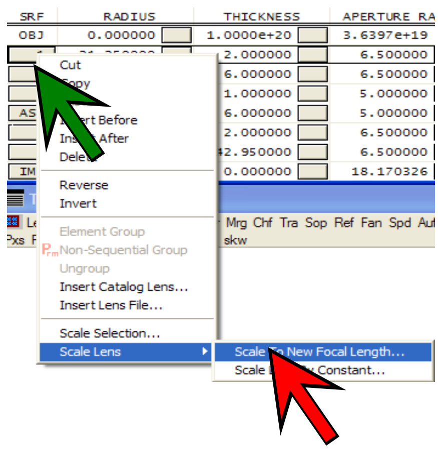
LENS ENTRY

1. Using any version of OSLO (including EDU) open the lens in the public directory: **C:ProgramFiles\OSLO\EDU64\public\len\demo\edu** with the file name **demotrip.len**

   Save it in a newly created private directory: **C:ProgramFiles\OSLO\EDU64\private\len\EDU_Tutorial** with the same file name.



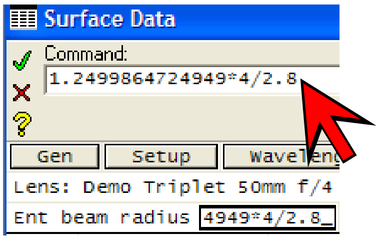
2. If it is not open already, open the surface data spreadsheet by clicking on the blue lens icon in the main window toolbar.**[lse]**



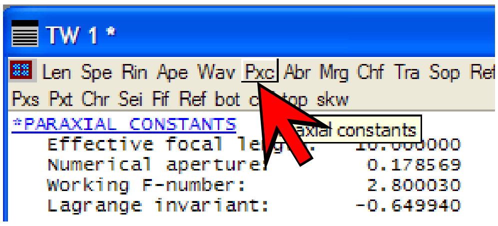
3. Scale the lens to focal length 10 mm by right-clicking on any surface number button, and selecting **Scale Lens** ►**Scale to**

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 1.785714]**

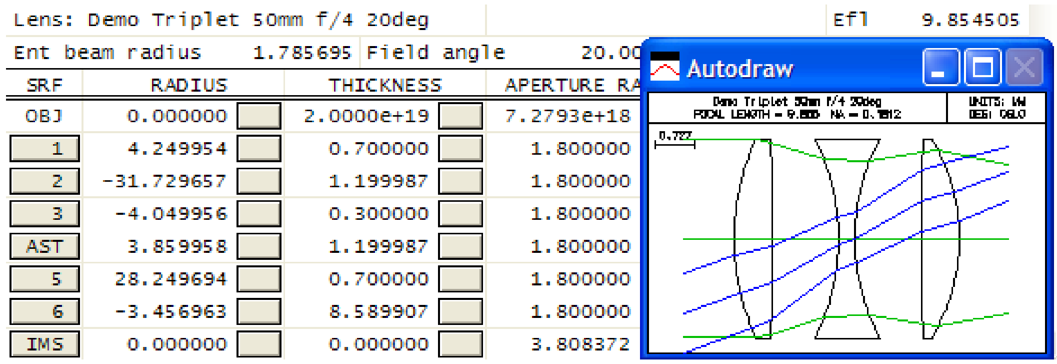


5. Verify the f-number using the text window header **Pxc. [pxc]**

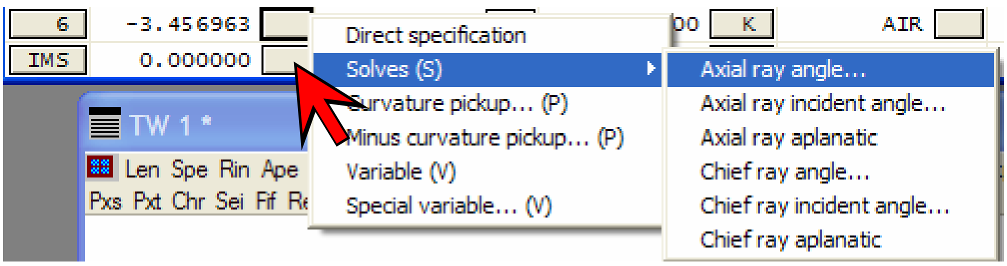


6. Increase the aperture radii of all surfaces 1 to 6 to 1.8 **[ap 1 1.8] [ap 2 1.8].. [ap 6 1.8]**

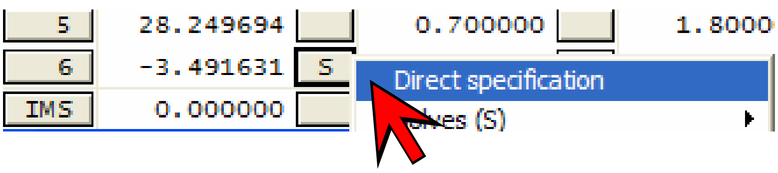
7. Increase the thickness of the first element to 0.7 mm, of the second element to 0.3 mm, and of the third element to 0.7 mm. **[th 1 0.7]**, **[th 3 0.3]**, **[th 5 0.7]**



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



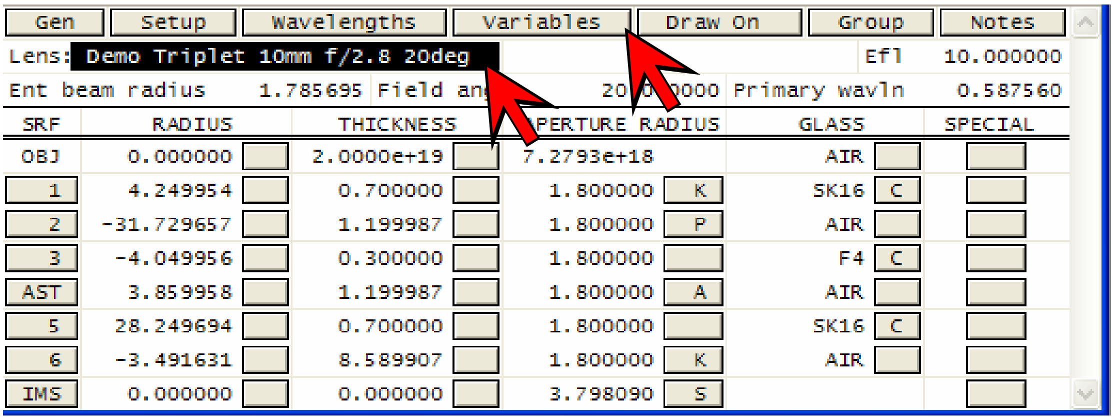
Right-click on the grey RADIUS button for surface number 6, and select **Solves(S) ▶ Axial ray angle ... ▶ Enter solve value:** `-0.1785714` (note that this is -0.1 times the entrance beam radius)



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 -0.1785714;csd 6 or **rd 6 -3.491632]**

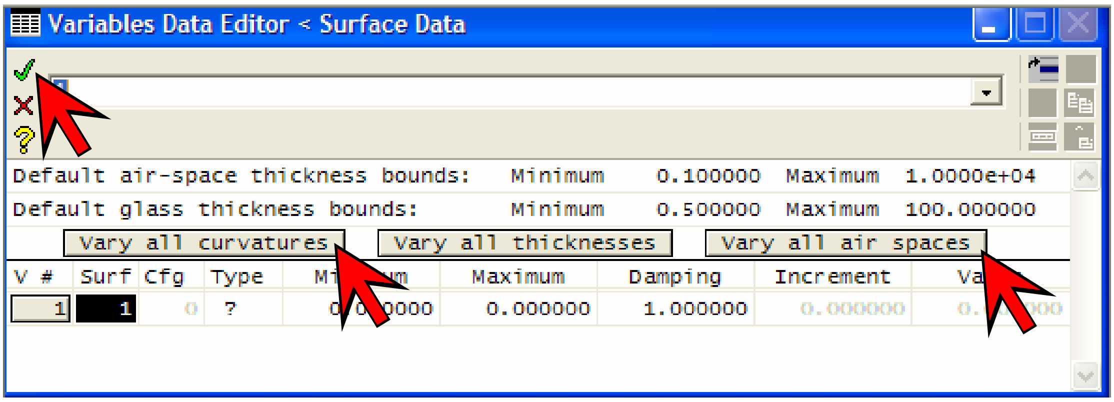
10. Verify the effective focal length is 10mm using the command **Pxc.**

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



and save the lens as **Triplet10mm_Start.len** in the directory **C:ProgramFiles\OSLO\EDU64\private\len\EDU_Tutorial.**

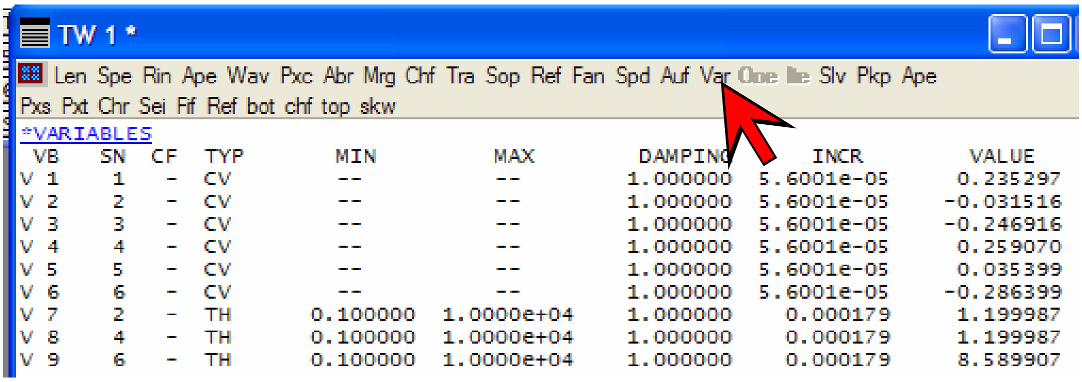
12. Open the variables data editor: click on the button labelled **Variables** in the lens data editor. **[vse]**



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

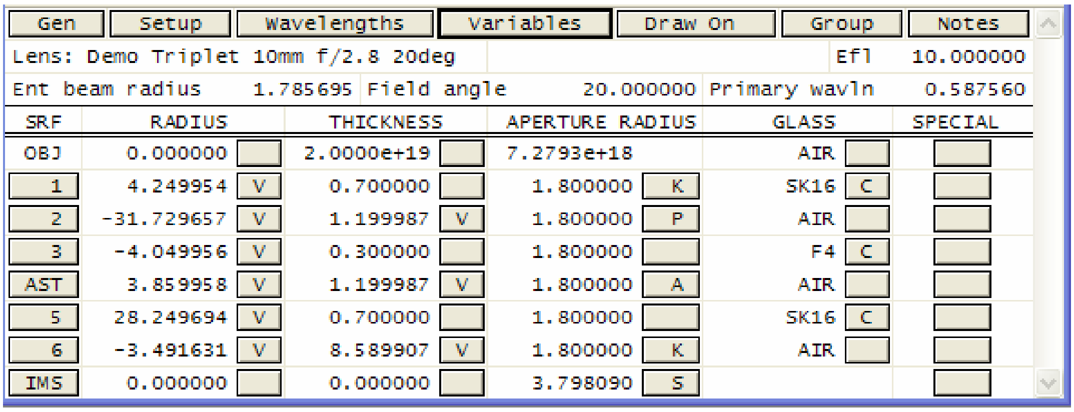
14. Close the variables spreadsheet with the green tick:

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



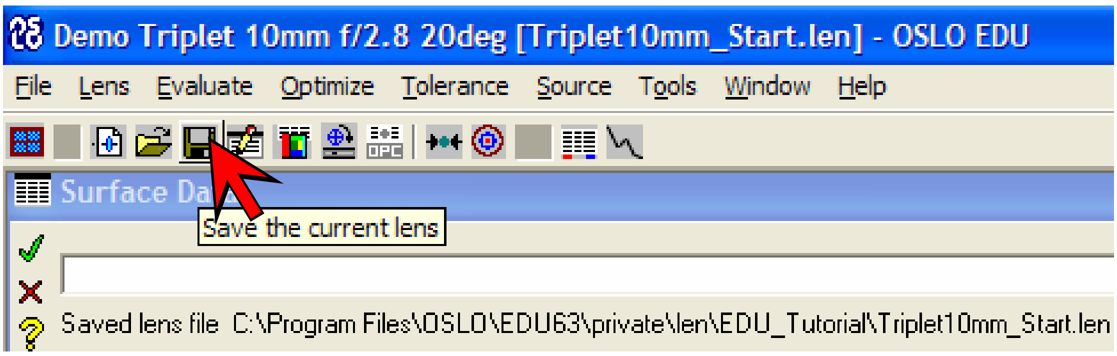
VB	SN	CF	TYP	MIN	MAX	DAMPING	INCR	VALUE
V 1	1	-	CV	--	--	1.000000	5.6001e-05	0.235297
V 2	2	-	CV	--	--	1.000000	5.6001e-05	-0.031516
V 3	3	-	CV	--	--	1.000000	5.6001e-05	-0.246916
V 4	4	-	CV	--	--	1.000000	5.6001e-05	0.259070
V 5	5	-	CV	--	--	1.000000	5.6001e-05	0.035399
V 6	6	-	CV	--	--	1.000000	5.6001e-05	-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 surface data spreadsheet should have the following appearance, with a **V** against each variable parameter:



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			

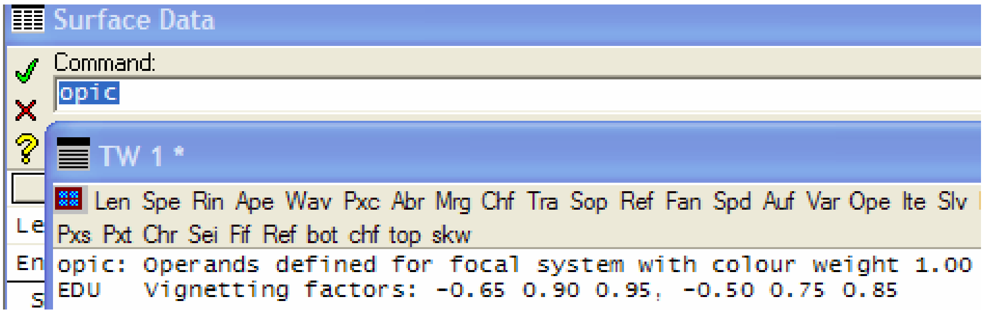
16. Save the lens again by clicking on the icon in the main window header. **[save]**



This completes the section duplicated in the document "Optimization Tutorial using OSLO Light."

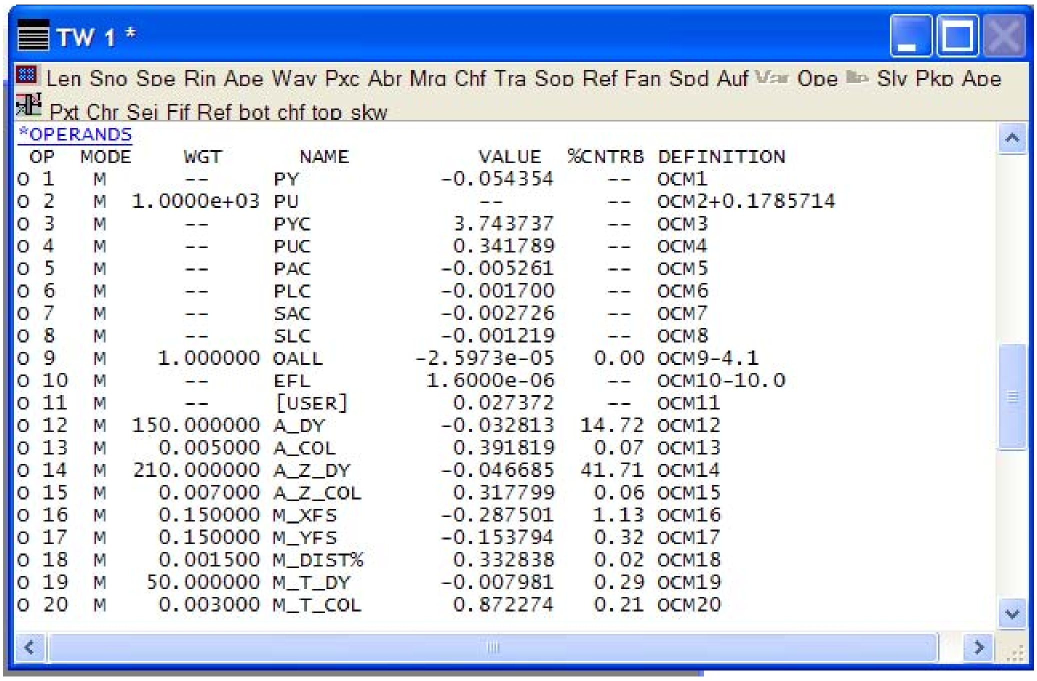
OPTIMISATION USING THE OPIC ERROR FUNCTION

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.



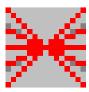
Note the message in the text window. The "Vignetting factors" on the second line are the (relative) values of **ymin, ymax** and **xmax** for the two off-axis points, at (relative) field heights of 0.7 and 1.0 respectively. These figures will be used to set the rays drawn in the lens drawing conditions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

18. Click on the text window header **Ope** to list the operands **[ope]**



OP	MODE	WGT	NAME	VALUE	%CNTRB	DEFINITION
O 1	M	--	PY	-0.054354	--	OCM1
O 2	M	1.0000e+03	PU	--	--	OCM2+0.1785714
O 3	M	--	PYC	3.743737	--	OCM3
O 4	M	--	PUC	0.341789	--	OCM4
O 5	M	--	PAC	-0.005261	--	OCM5
O 6	M	--	PLC	-0.001700	--	OCM6
O 7	M	--	SAC	-0.002726	--	OCM7
O 8	M	--	SLC	-0.001219	--	OCM8
O 9	M	1.000000	OALL	-2.5973e-05	0.00	OCM9-4.1
O 10	M	--	EFL	1.6000e-06	--	OCM10-10.0
O 11	M	--	[USER]	0.027372	--	OCM11
O 12	M	150.000000	A_DY	-0.032813	14.72	OCM12
O 13	M	0.005000	A_COL	0.391819	0.07	OCM13
O 14	M	210.000000	A_Z_DY	-0.046685	41.71	OCM14
O 15	M	0.007000	A_Z_COL	0.317799	0.06	OCM15
O 16	M	0.150000	M_XFS	-0.287501	1.13	OCM16
O 17	M	0.150000	M_YFS	-0.153794	0.32	OCM17
O 18	M	0.001500	M_DIST%	0.332838	0.02	OCM18
O 19	M	50.000000	M_T_DY	-0.007981	0.29	OCM19
O 20	M	0.003000	M_T_COL	0.872274	0.21	OCM20

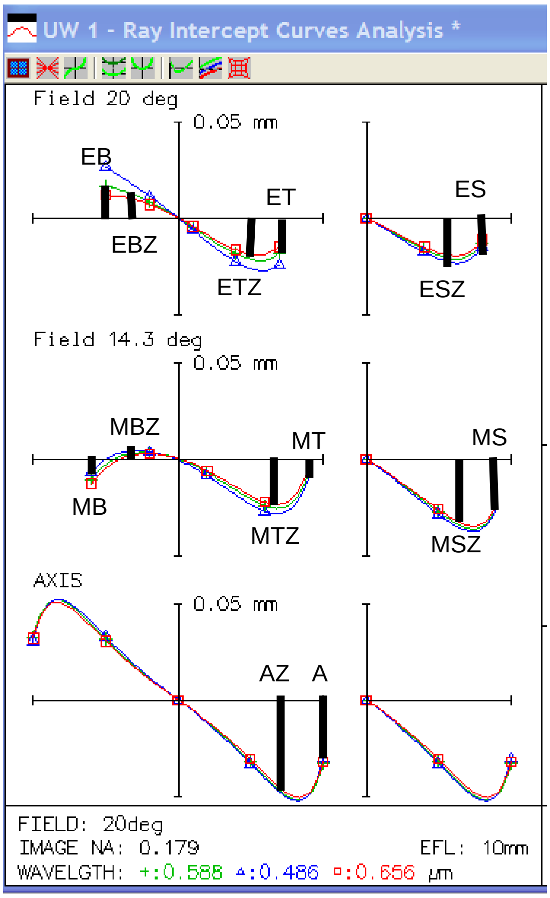
19. Click on the RIC (ray intercept coordinate) report graphics icon in the graphics window to get the ray trace results for the lens. The left-hand part of the diagram is shown below.



The black bars on the diagram illustrate the transverse aberrrations which are controlled by the OPIC error function. Also the name of each operand is shown. For example, the 19th operand listed above has the name M_T_DY. This refers to:

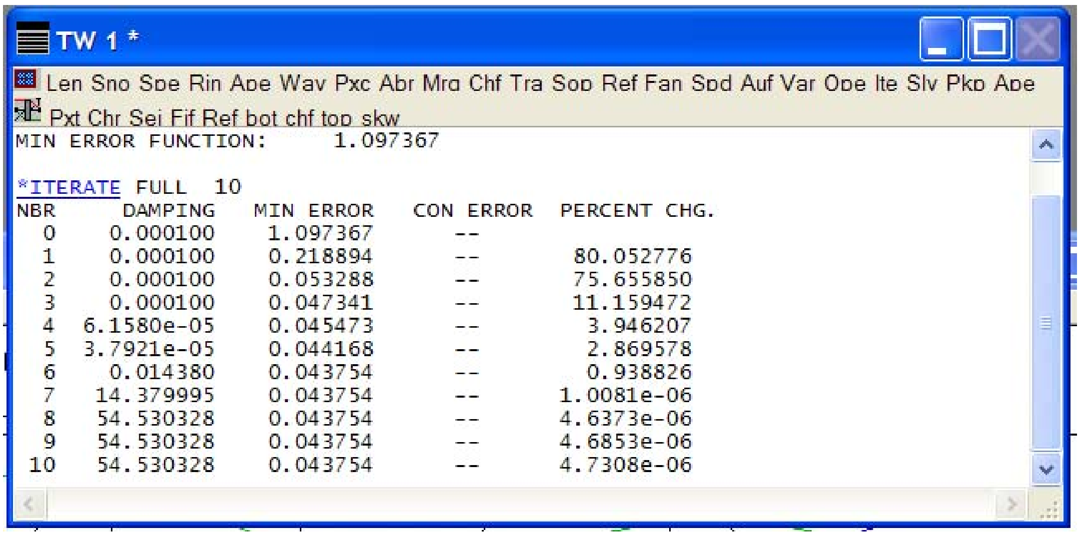
- M the field point FBY = 0.7 (mid-field)
- T the top of the pupil (Y = +1)
- DY the transverse aberrration in the Y direction.

In the diagram here it is represented by the bar labelled **MT**.



20. Scroll down to the bottom of the list of operands to find the starting error function.

21. Optimise ("iterate") 10 times by clicking once on the text window header **Ite** once **[ite]**



MIN ERROR FUNCTION: 1.097367

*ITERATE FULL 10

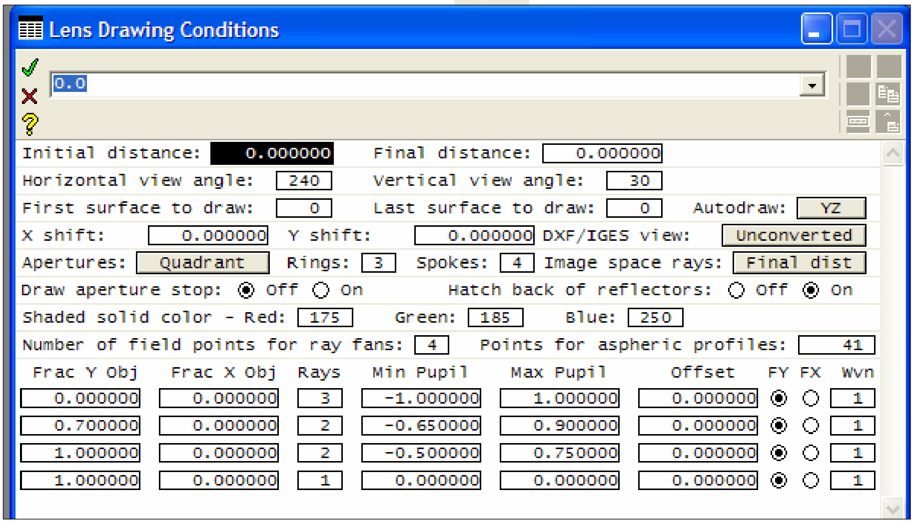
NBR	DAMPING	MIN ERROR	CON ERROR	PERCENT CHG.
0	0.000100	1.097367	--	
1	0.000100	0.218894	--	80.052776
2	0.000100	0.053288	--	75.655850
3	0.000100	0.047341	--	11.159472
4	6.1580e-05	0.045473	--	3.946207
5	3.7921e-05	0.044168	--	2.869578
6	0.014380	0.043754	--	0.938826
7	14.379995	0.043754	--	1.0081e-06
8	54.530328	0.043754	--	4.6373e-06
9	54.530328	0.043754	--	4.6853e-06
10	54.530328	0.043754	--	4.7308e-06

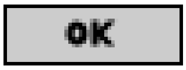
No further improvement is necessary.

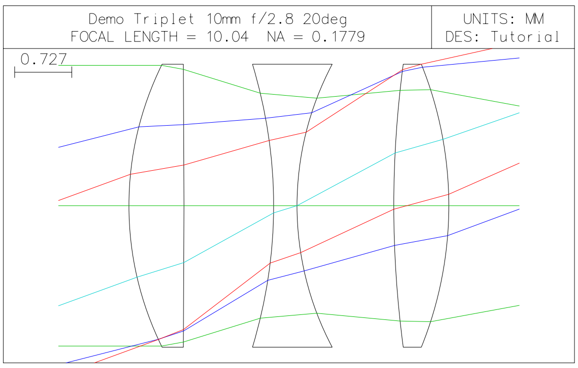
22. Save as **Triplet10mm_final.len** in the same directory as before.

DRAWING THE FINAL DESIGN

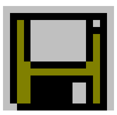
23. From the **Lens** menu header and select **Lens Drawing Conditions ...**. **[uoc drl]** In the spreadsheet:
    - After **Number of field points for ray fans:** enter **4**.
    - Under the column **Frac Y Obj** type **1.0** in the fourth row.
    - Under the column **Rays** type **2** in the second 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: 



24. Draw the lens:
- From the **Lens** menu header select **Lens Drawing ...** ► **System**
- Accepting all the defaults, click on 



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

25. Save the lens again to preserve these ray drawings. 

EVALUATING THE FINAL DESIGN

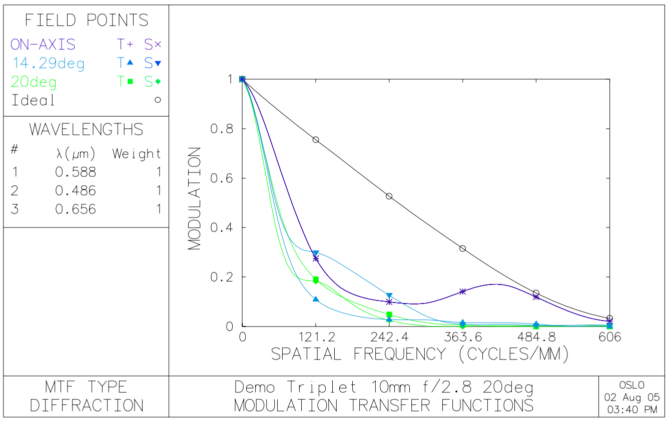
MODULATION TRANSFER FUNCTION

This is the most important measure of resolution used in lens design. The modulation transfer function is reduced by aberrations, but the “ideal” MTF is the MTF of a perfect system of the same aperture and wavelength, which represents the upper limit of what can be achieved - the so-called diffraction limit. The ideal MTF becomes zero at a spatial frequency known as the diffraction limit.

26. 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.

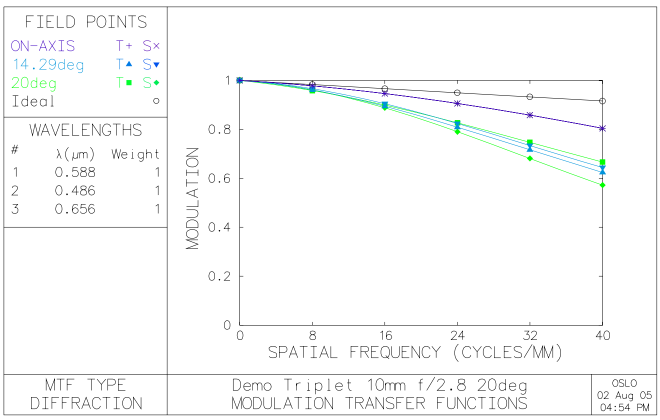


27. From the **Evaluate** menu header select **Transfer function ► Through frequency report graphic ...** and enter the figure calculated (**`606.0`**) in the box labelled **Maximum frequency**.

    Click on **OK**

    This gives a plot of the MTF out to the diffraction limit.
    [rpt_tfr 606.0]

28. 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

Vignetting is the measure of the fall-off in brightness towards the edge of the field, relative to the centre, and is calculated very easily with OSLO EDU.

29. To define the object point at full field, in the command window type: **`sop 1 0 0`**

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

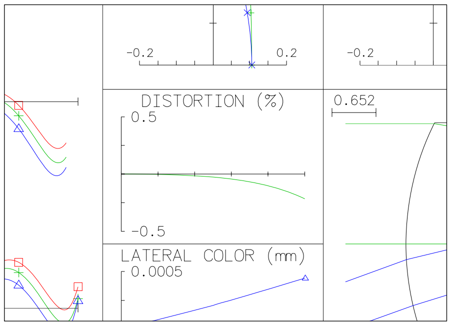
```
*SET OBJECT POINT
         FBY          FBX          FBZ
       1.000000       --           --
        FYRF         FXRF          FY           FX
         --           --           --           --
   YC           XC           YFS          XFS          OPL     REF SPH RAD
 3.606943       --      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

31. Note the “Per cent weighted ray transmission” value of 58.6%. Hence the brightness reduction is 41.4% at the extreme edge of the field.

DISTORTION

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

33. The graph of distortion is near the middle of the window. Note that in this case 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.

LENS PRESCRIPTION

The prescription of this lens is listed by clicking on the commands **Len** and **Pxc** in the text window: **[len;pxc]**

```
*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
```

Note: In this document, OSLO commands equivalent to the entries described are included in **this typeface.**

APPENDICES

1. COPYING AND COMPILING OPIC

- On the CD provided, open the directory **CCL**
- Copy the file **optim_ic_EDU.ccl** to the directory **C:ProgramFiles\OSLO\EDU64\private\ccl**

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, to compile all private CCL files.
- 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

2. OPIC DOCUMENTATION

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

OPIC for OSLO EDU

Contributed by Brian Blandford

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:

1. The mid-field distortion value is incorrect for ray aiming mode = "wide angle".
2. 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.