1 Paraxial system layout

a) Suppose a divergent ray bundle with numerical aperture of NA = 0.2 at the wavelength λ = 500 nm. Establish a first paraxial lens with a focal length to get a collimated beam with diameter 24 mm.

b) After a distance of 10 mm a second paraxial lens with focal length f2 = 30 mm focusses the ray. Behind the focal point a third paraxial lens should collimated the beam again for a diameter of 36 mm.

c) Now in a distance of 20 mm a focussing paraxial lens with focal length f = 100 is added. Finally a negative lens with f = -70 mm is added in an appropriate distance to change the numerical aperture in the image space to 0.05. Find the final image distance. What is the magnification of the system ?

Solution:

a) Wavelength and numerical aperture are inserted. Then we set the focal length by a pickup to have the same value as the first object distance. This guarantees a collimated output beam. In the merit function a PARY value of D/2 = 12 mm is required, the first distance is variable. Alternatively without using the optimization, the value can be calculated by hand with tan(u) = sin(u)/cos(u) = D/2/f = 58.788 mm or approximated with the slider.

Lens Data Editor

Edit Solves View Help

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	Par 1 (unused)	Par 2 (unused)	Par 3 (unused)	Par 4 (unused)
OBJ	Standard		Infinity	58.78775 V		0.00000	0.00000					
STO	Paraxial			0.00000		12.00000			58.78775 P	1		
IMA	Standard		Infinity	-		12.00000	0.00000					

Merit Function Editor: 5.186251E-011

Edit Design Tools View Help

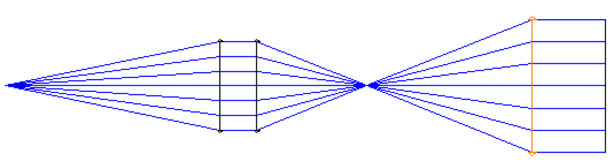
Oper #	Type	Surf	Wave	Hx	Hy	Px	Py			Target	Weight
1: PARY	PARY	2	1	0.00000	0.00000	0.00000	1.00000			12.00000	1.00000

b) The 3rd lens must have a focal length of 36/24 x 30 = 45 mm. The air distances are correspondingly.

Lens Data Editor

Edit Solves View Help

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0 (unused)	Focal Length
OBJ	Standard		Infinity	58.78775 V		0.00000	0.00000		
STO	Paraxial			10.00000		12.00000			58.78775 P
2	Paraxial			30.00000		12.00000			30.00000
3	Standard		Infinity	45.00000		0.00000	0.00000		
4	Paraxial			20.00000		18.00000			45.00000
IMA	Standard		Infinity	-		18.00000	0.00000		



```
Normalized X Field Coord (Hx) :      0.0000000000
Normalized Y Field Coord (Hy) :      0.0000000000
Normalized X Pupil Coord (Px) :      0.0000000000
Normalized Y Pupil Coord (Py) :      1.0000000000

Real Ray Trace Data:

Surf        X-coordinate        Y-coordinate        Z-coordinate
OBJ  -0.0000000000E+000  -0.0000000000E+000   0.0000000000E+000
  1   0.0000000000E+000   1.2000000000E+001   0.0000000000E+000
  2   0.0000000000E+000   1.2000000000E+001   0.0000000000E+000
  3   0.0000000000E+000   0.0000000000E+000   0.0000000000E+000
  4   0.0000000000E+000  -1.8000000000E+001   0.0000000000E+000
  5   0.0000000000E+000  -1.8000000000E+001   0.0000000000E+000
```

c) A second optimization selects the distance of lens 4 to obtain the numerical aperture by PARB to be 0.05. The image distance is obtained by QUICK FOCUS. Thelens data ar

Lens Data Editor

Edit Solves View Help

Surf:Type		Comment	Radius	Thickness		Glass	Semi-Diameter	Conic	Par 0(unused)	Focal Length	
OBJ	Standard		Infinity	58.78775			0.00000	0.00000			
STO	Paraxial			10.00000			12.00000			58.78775	P
2	Paraxial			30.00000			12.00000			30.00000	
3	Standard		Infinity	45.00000			0.00000	0.00000			
4	Paraxial			20.00000			18.00000			45.00000	
5	Paraxial			49.46880	V		18.00000			100.00000	
6	Paraxial			181.68480			9.09562			-70.00000	
IMA	Standard		Infinity	-			1.4211E-014	0.00000			

Merit Function Editor: 3.078239E-012

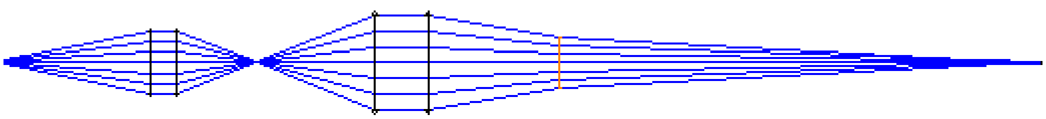
Edit Design Tools View Help

Oper #	Type	Surf	Wave	Hx	Hy	Px	Py			Target	Weight	Value
1: PARB	PARB	7	1	0.00000	0.00000	0.00000	1.00000			0.05000	1.00000	0.05000

```
Normalized X Field Coord (Hx) :      0.0000000000
Normalized Y Field Coord (Hy) :      0.0000000000
Normalized X Pupil Coord (Px) :      0.0000000000
Normalized Y Pupil Coord (Py) :      1.0000000000

Real Ray Trace Data:

Surf      X-coordinate       Y-coordinate       Z-coordinate        X-cosine       Y-cosine
OBJ  -0.0000000000E+000 -0.0000000000E+000  0.0000000000E+000   0.0000000000   0.2000000000
  1   0.0000000000E+000  1.2000000000E+001  0.0000000000E+000   0.0000000000   0.0000000000
  2   0.0000000000E+000  1.2000000000E+001  0.0000000000E+000   0.0000000000  -0.3713906764
  3   0.0000000000E+000  0.0000000000E+000  0.0000000000E+000   0.0000000000  -0.3713906764
  4   0.0000000000E+000 -1.8000000000E+001  0.0000000000E+000   0.0000000000   0.0000000000
  5   0.0000000000E+000 -1.8000000000E+001  0.0000000000E+000   0.0000000000   0.1771529983
  6   0.0000000000E+000 -9.0956167796E+000  0.0000000000E+000   0.0000000000   0.0500000000
  7   0.0000000000E+000  1.4210854715E-014  0.0000000000E+000   0.0000000000   0.0500000000
```



The magnification is 0.2 / 0.05 = 4 .

2 Singlet II

Establish a single lens with the following data:

wavelength:	λ = 546.07 nm
object distance	100 mm
thickness of the lens, made of N-BK7	t = 8 mm
front radius of curvature	R1 = 45 mm
rear radius of curvature	R2 = -100 mm
numerical aperture in the object space	NA = 0.07
lens diameter	24 mm

a) Fix the final distance in the paraxial image plane. Create a layout plot

b) Calculate the spot diagram and the transverse ray aberrations.
What is the spot size ?
Is the system diffraction limited ?
What residual aberration is obtained ?
Are also higher order aberrations obtained ?
Determine the image sided numerical aperture by calculating the marginal ray.

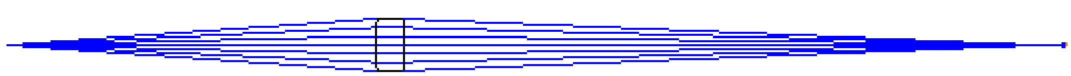
c) Add an off axis field point with height y = 10 mm.
Fix the pupil of the system at the rear surface of the lens
Find the best plane for gathering the image. Is the distance increased or decreased ?
Calculate the layout and the spot diagram. What is the dominating aberration for the field point now ?

d) Add a second lens and give both lenses roughly the same focal power by keeping the system focal length constant.
Is the system performance improved and diffraction limited ?
Calculate the Seidel aberrations and discuss the opportunities of improving the system for spherical aberration.
Reverse the first lens and reduce the numerical aperture to NA = 0.04. Calculate the performance now.
Calculate the point spread function and determine the Strehl ratio on axis.

Solution

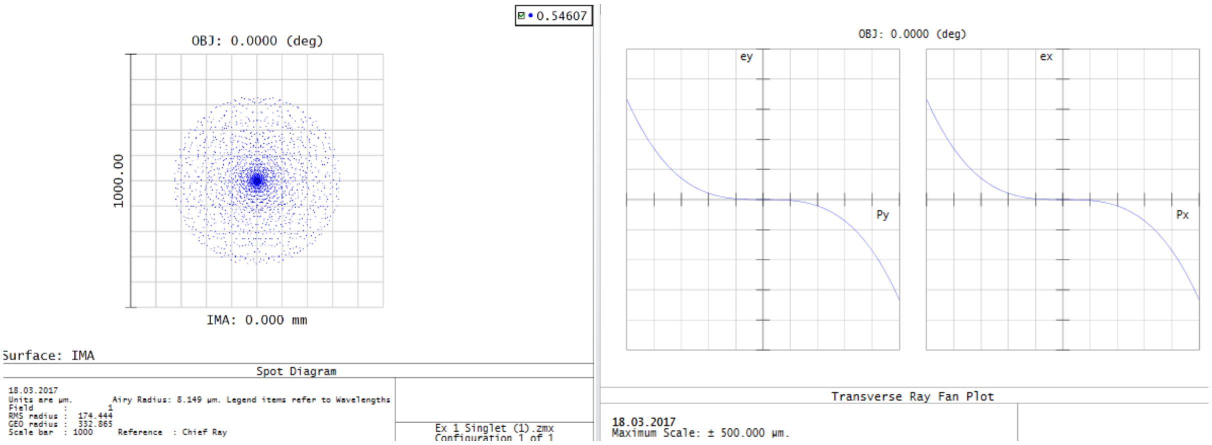
a) Starting setup:

	Surf:Type		Comment	Radius	Thickness		Material	Coating	Clear Semi-Di	
0	OBJECT	Standard		Infinity	100.0000				0.0000	
1	(aper)	Standard		50.0000	8.0000		N-BK7		12.0000	U
2	STOP (a	Standard		-100.00...	179.7783	M			12.0000	U
3	IMAGE	Standard		Infinity	-				0.3330	



b) The spot radius rms value is 175 μm and is far above the Airy radius of 8.1 mm.
The image sided numerical aperture is NA = 0.0408, the paraxial value is NAi = 0.0389
The residual aberration is pure spherical aberration.

By inspection the Zernike coefficients it is found c9 = 0.995 and c16 = 0.006, therefore we have dominating 3rd order spherical aberration.



4: Single Ray Trace

Settings 3 x 4 Thin

```
Title:
Date : 18.03.2017


Units       :    Millimeters
Wavelength  :    0.546070    µm
Coordinates :    Local
Direction cosines are after refraction or reflection from the surface or object.
Angles are in degrees.

Normalized X Field Coord (Hx) :       0.0000000000
Normalized Y Field Coord (Hy) :       0.0000000000
Normalized X Pupil Coord (Px) :       0.0000000000
Normalized Y Pupil Coord (Py) :       1.0000000000

Real Ray Trace Data:

Surf        X-coordinate        Y-coordinate        Z-coordinate       X-cosine       Y-cosine       Z-cosine
OBJ    -0.0000000000E+00   -0.0000000000E+00    0.0000000000E+00   0.0000000000   0.0700000000   0.9975469914
  1     0.0000000000E+00    7.0522885588E+00    4.9984620141E-01   0.0000000000  -0.0027990626   0.9999960826
  2     0.0000000000E+00    7.0319879893E+00   -2.4755068211E-01   0.0000000000  -0.0408765008   0.9991642066
  3     0.0000000000E+00   -3.3299611298E-01    0.0000000000E+00   0.0000000000  -0.0408765008   0.9991642066

Paraxial Ray Trace Data:

Surf        X-coordinate        Y-coordinate        Z-coordinate       X-cosine       Y-cosine       Z-cosine
OBJ    -0.0000000000E+00   -0.0000000000E+00    0.0000000000E+00   0.0000000000   0.0700000000   0.9975469914
  1     0.0000000000E+00    7.0172132847E+00    0.0000000000E+00   0.0000000000  -0.0017301033   0.9999985034
  2     0.0000000000E+00    7.0033724377E+00    0.0000000000E+00   0.0000000000  -0.0389260714   0.9992420933
  3     0.0000000000E+00   -1.7763568394E-15    0.0000000000E+00   0.0000000000  -0.0389260714   0.9992420933
```

Settings 3 x 4 Thin

```
Variance                      :     3.02546207 waves squared
Strehl Ratio (Est)            :     0.00000000

RMS fit error                 :     0.00000000 waves
Maximum fit error             :     0.00000000 waves

Z   1     1.96094219   :   1
Z   2     0.00000000   :   (p) * COS (A)
Z   3     0.00000000   :   (p) * SIN (A)
Z   4     2.95016949   :   (2p^2 - 1)
Z   5     0.00000000   :   (p^2) * COS (2A)
Z   6     0.00000000   :   (p^2) * SIN (2A)
Z   7     0.00000000   :   (3p^2 - 2) p * COS (A)
Z   8     0.00000000   :   (3p^2 - 2) p * SIN (A)
Z   9     0.99512679   :   (6p^4 - 6p^2 + 1)
Z  10     0.00000000   :   (p^3) * COS (3A)
Z  11     0.00000000   :   (p^3) * SIN (3A)
Z  12     0.00000000   :   (4p^2-3) p^2 * COS (2A)
Z  13     0.00000000   :   (4p^2-3) p^2 * SIN (2A)
Z  14     0.00000000   :   (10p^4 - 12p^2 + 3) p * COS (A)
Z  15     0.00000000   :   (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16     0.00594644   :   (20p^6 - 30p^4 + 12p^2 - 1)
Z  17     0.00000000   :   (p^4) * COS (4A)
Z  18     0.00000000   :   (p^4) * SIN (4A)
Z  19     0.00000000   :   (5p^2 - 4) p^3 * COS (3A)
Z  20     0.00000000   :   (5p^2 - 4) p^3 * SIN (3A)
Z  21     0.00000000   :   (15p^4 - 20p^2 + 6) p^2 * COS (2A)
Z  22     0.00000000   :   (15p^4 - 20p^2 + 6) p^2 * SIN (2A)
Z  23     0.00000000   :   (35p^6 - 60p^4 + 30p^2 - 4) p * COS (A)
Z  24     0.00000000   :   (35p^6 - 60p^4 + 30p^2 - 4) p * SIN (A)
Z  25     0.00004732   :   (70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)
```

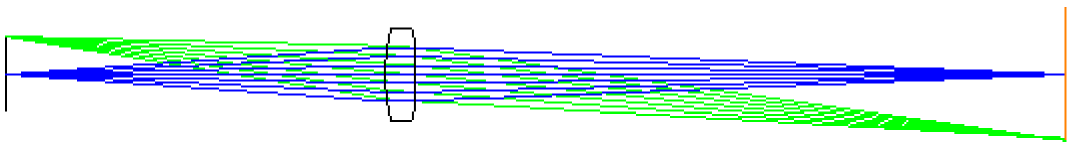
c)
The distance is decreased by approx. 8 mm.

Lens Data

Update: Editors Only

Surface 3 Properties

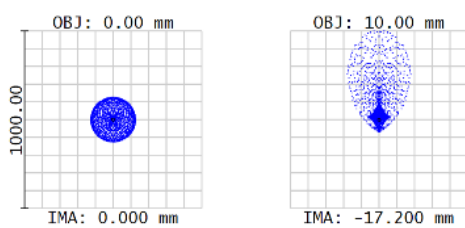
	Surf:Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Di	
0	OBJECT	Standard		Infinity	100.0000			10.0000	
1	(aper)	Standard		50.0000	8.0000	N-BK7		12.0000	U
2	STOP (a	Standard		-100.00...	171.5061			12.0000	U
3	IMAGE	Standard		Infinity	-			17.2702	



From the spot diagram it cannor be distinguished between defocus/curvature, astigmatism and coma. With the Zernikes oefficients, we get:

curvature	c4 = 0.95
astigmatism	c5 = -2.87
coma	c8 = -1.81

This means, the astigmatism is the largest contribution.



Surface: IMA

Spot Diagram

18.03.2017
Units are µm. Airy Radius: 8.149 µm. Legend items refer to Wavelengths
Field : 1 2
RMS radius : 93.665 148.738
GEO radius : 126.099 501.223

Ex 1 Sing

```
Z   1      -0.04184837  :   1
Z   2       0.00000000  :   (p) * COS (A)
Z   3      -3.59217247  :   (p) * SIN (A)
Z   4       0.94674417  :   (2p^2 - 1)
Z   5      -2.86686119  :   (p^2) * COS (2A)
Z   6       0.00000000  :   (p^2) * SIN (2A)
Z   7       0.00000000  :   (3p^2 - 2) p * COS (A)
Z   8      -1.81457447  :   (3p^2 - 2) p * SIN (A)
Z   9       0.99464944  :   (6p^4 - 6p^2 + 1)
Z  10       0.00000000  :   (p^3) * COS (3A)
Z  11      -0.00913479  :   (p^3) * SIN (3A)
Z  12      -0.00299627  :   (4p^2-3) p^2 * COS (2A)
Z  13       0.00000000  :   (4p^2-3) p^2 * SIN (2A)
Z  14       0.00000000  :   (10p^4 - 12p^2 + 3) p * COS (
Z  15      -0.01263220  :   (10p^4 - 12p^2 + 3) p * SIN (
Z  16       0.00610625  :   (20p^6 - 30p^4 + 12p^2 - 1)
```