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Solution of Exercises
Lecture Optical design with Zemax– Part 3

3 Aberrations

3.1 Performance of an achromate

Load a classical achromate out of a vendor catalog with focal length f = 100 mm.
a) What is the numerical aperture of the system in the image side ? Is the system diffraction limited ?
b) Determine the longitudinal aberrations for the colors eF'C'. What is the largest spherical aberration in the green ? What is the height of the corresponding ray in the pupil ? What is the largest difference of the axial color aberration ?
c) Calculate the Seidel surface contributions of the system in the desired orientation and for the reversed lens.
d) Determine the range of finite field angles, for which the original achromate is diffraction limited, if λ = 546 nm and a reduced aperture diameter of 15 mm is considered.

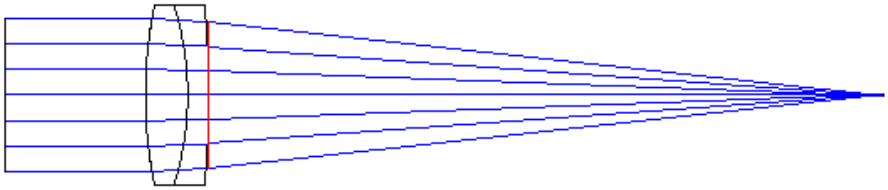
Solution:

a) Setup (Melles Griot, AAP-100.0 - 25.4)

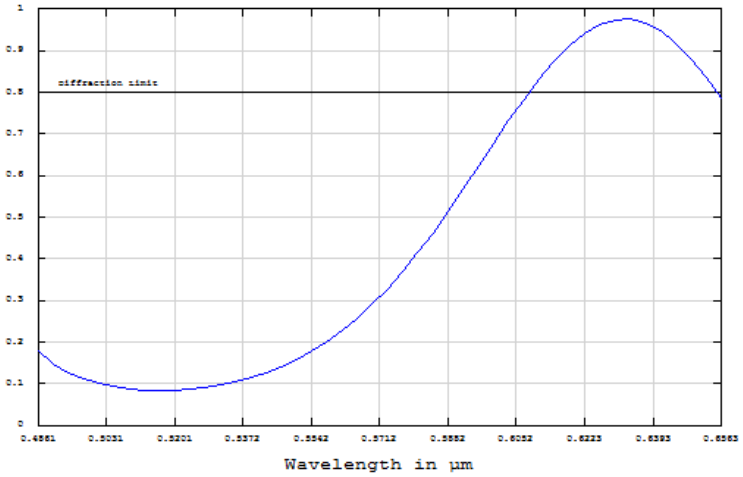
Lens Data Editor

Edit Solves View Help

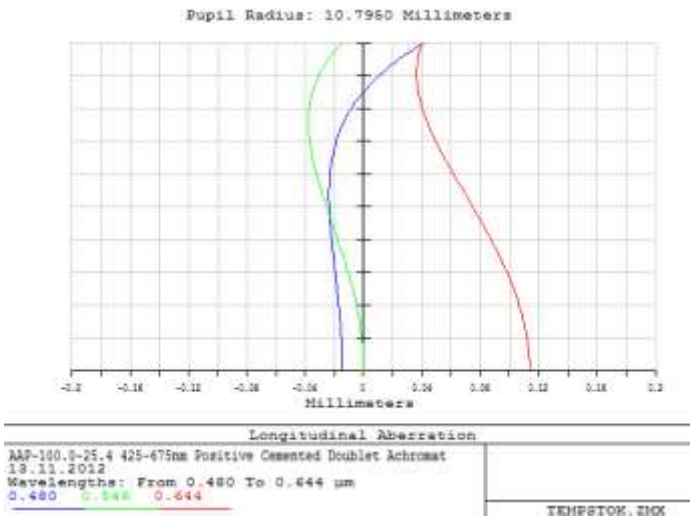
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.0000000	
*	Standard	AAP-100.0-25.4	62.0050000		6.0000000		N-BK7		12.7000000	U
2*	Standard		-42.379000		3.0000000		SF2		12.7000000	U
3*	Standard		-133.28400		95.6878729	M			12.7000000	U
IMA	Standard		Infinity		-				4.487E-003	



The numerical aperture is NA = 0.107. The system is diffraction limited for wavelength λ > 608 nm (rms vs wavelength, Strehl criterion, 9 rays, 100 wavelengths):



b) Take eF'C' as wavelengths and calculate the longitudinal aberration curves.



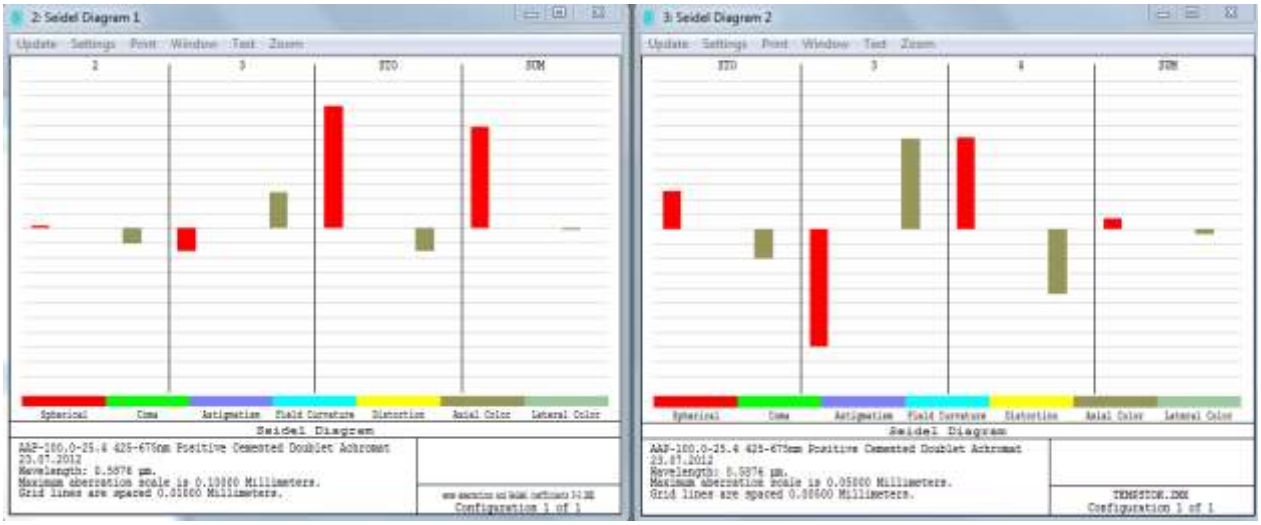
The largest spherical aberration in the green can be obtained by the text output and is s' = -0.0377 mm. this value corresponds to a relative pupil height of 0.76.
From the first row of the text output we get the maximum difference along the axis between blue and red of 128.4 µm.

3: Longitudinal Aberration 2

Update Settings Print Window

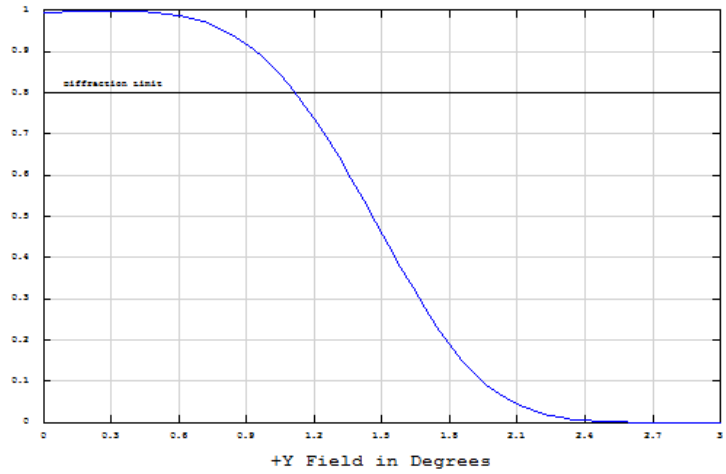
```
Listing of Longitudinal Aberration Data

File : C:\Users\Gross\Documents\ZEMAX\SAMPLES\TEMPSTOK
Title: AAP-100.0-25.4 425-675nm Positive Cemented Doub
Date : 13.11.2012


Units are Millimeters.

Rel. Pupil      0.4800      0.5461      0.6438
     0.0000 -1.462E-002 -3.175E-006  1.138E-001
     0.0100 -1.463E-002 -1.270E-005  1.138E-001
     0.0200 -1.465E-002 -5.079E-005  1.138E-001
     0.0300 -1.468E-002 -1.142E-004  1.137E-001
     0.0400 -1.472E-002 -2.030E-004  1.135E-001
     0.0500 -1.478E-002 -3.169E-004  1.134E-001
```

c) Seidel aberration bar chart for the original and the reversed system:

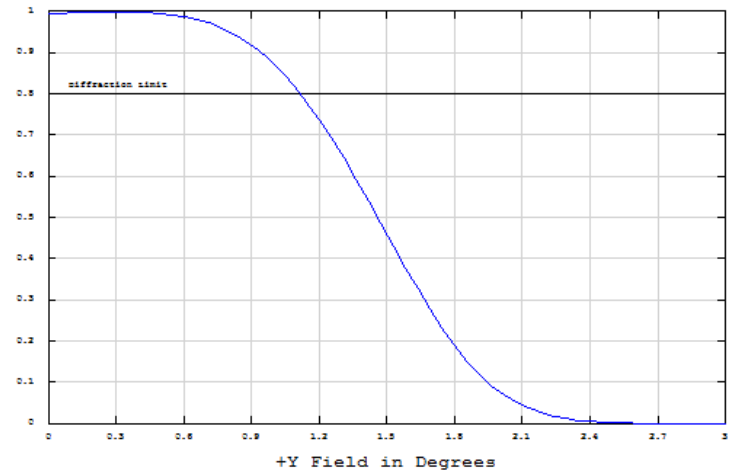


It is seen, that the the system is quite bad for the reversed lens. Therefore the catalog component should be used only with incoming collimated light.

d) With the rms-menu vs. field size and the Strehl ratio criterion with more rays, we get the following drawing after a quick focus for the axis point only:



It can be seen, that the diffraction limit is violated for field angles w > 1.1°.



It can be seen, that the diffraction limit is violated for field angles w > 1.1°.

3.2 Aplanatic lens

Consider a collimated incoming beam with wavelength 500 nm and diameter 10 mm. This bundle should be focussed by a perfect lens of focal length f = 50 mm.
a) Place an aplanatic-concentric lens shortly behind the ideal lens with the material SF57. What is the resulting numerical aperture in the image space ? Show at least two different methods to find the best image position.
b) Show that the spherical aberration of this setup is exactly zero for all orders.
c) Aplanatic means, that the linear coma vanishes and the imaging is free of coma for a small but finite field size. Show this property by using a small field of 2° for the current system. What is the largest present aberration ?

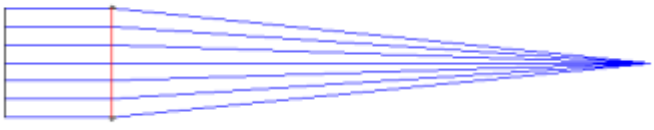
Solution:

The initail focussing lens is established as follows:

Lens Data Editor

Edit Solves View Help

		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard		Infinity	Infinity		0.0000000	0.0000000		
1	Standard		Infinity	10.0000000		5.0000000	0.0000000		
STO	Paraxial			0.0000000		5.0000000			50.0000000
3	Standard		Infinity	50.0000000		5.0000000	0.0000000		
IMA	Standard		Infinity	-		0.0000000	0.0000000		

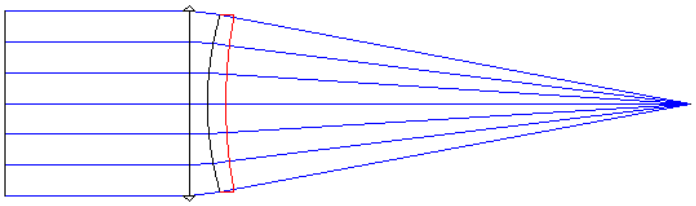


a) A lens with thickness 1 mm is placed 1 mm behid the lens. The first surface is made aplanatic by a solve, the second surface is mad concentric by choosing the solve

Lens Data Editor

Edit Solves View Help

Surf:Type	Comment	Radius		Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ Standard		Infinity		Infinity		0.0000000	0.0000000		
1 Standard		Infinity		10.0000000		5.0000000	0.0000000		
STO Paraxial				0.0000000		5.0000000			50.0000000
3 Standard		Infinity		1.0000000		5.0000000	0.0000000		
4 Standard		17.0884803	A	1.0000000	SF57	4.8303111	0.0000000		
5 Standard		25.2392874	M	25.2392874		4.6898661	0.0000000		
IMA Standard		Infinity		-		1.776E-015	0.0000000		



If a single ray trace is performed, we get the direction cosine of the marginal ray to be 0.1858.

3: Ray Trace

Update Settings Print Window

```
Ray Trace Data

File : C:\Gross\Lectures - Gross\Optical Design with Zemax\Aplanatic lens.ZMX
Title:
Date : 13.11.2012


Units       : Millimeters
Wavelength  : 0.500000 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
OBJ            Infinity           Infinity           Infinity   0.0000000000   0.0000000000
  1   0.0000000000E+000  8.0000000000E+000  0.0000000000E+000   0.0000000000   0.0000000000
  2   0.0000000000E+000  5.0000000000E+000  0.0000000000E+000   0.0000000000  -0.0985037190
  3   0.0000000000E+000  5.0000000000E+000  0.0000000000E+000   0.0000000000  -0.0985037190
  4   0.0000000000E+000  4.8303110655E+000  6.9688994649E-001   0.0000000000  -0.1858161068
  5   0.0000000000E+000  4.6898661252E+000  4.3955384906E-001   0.0000000000  -0.1858161068
  6   0.0000000000E+000  1.7763568394E-015  0.0000000000E+000   0.0000000000  -0.1858161068

Paraxial Ray Trace Data:
```

The best image position can be obtained by

1. Quick focus option
2. Solve at the last surface with marginal ray height 0
3. Pick up on the last (concentric) surface radius
4. Optimizing the last thickness as a variable with minimal spot size

b) If the Zernike polynomials are calculated, they are exactly zero for all orders.

2: Zernike Fringe Coefficients

Update Settings Print Window

```
Wavelength                    : 0.5000 µm
Peak to Valley (to chief)     :      0.00000001 waves
Peak to Valley (to centroid)  :      0.00000001 waves
RMS (to chief)                :      0.00000000 waves
RMS (to centroid)             :      0.00000000 waves
Variance                      :      0.00000000 waves s
Strehl Ratio (Est)            :      1.00000000

RMS fit error                 :      0.00000000 waves
Maximum fit error             :      0.00000001 waves

Z   1       0.00000000 :  1
Z   2       0.00000000 :  (p) * COS (A)
Z   3       0.00000000 :  (p) * SIN (A)
Z   4       0.00000000 :  (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       0.00000000 :  (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
Z  15       0.00000000 :  (10p^4 - 12p^2 + 3) p * SIN
Z  16       0.00000000 :  (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 * C(
Z  22       0.00000000 :  (15p^4 - 20p^2 + 6) p^2 * S
Z  23       0.00000000 :  (35p^6 - 60p^4 + 30p^2 - 4)
Z  24       0.00000000 :  (35p^6 - 60p^4 + 30p^2 - 4)
Z  25       0.00000000 :  (70p^8 - 140p^6 + 90p^4 - 2(
Z  26       0.00000000 :  (p^5) * COS (5A)
Z  27       0.00000000 :  (p^5) * SIN (5A)
Z  28       0.00000000 :  (6p^2 - 5) p^4 * COS (4A)
Z  29       0.00000000 :  (6p^2 - 5) p^4 * SIN (4A)
Z  30       0.00000000 :  (21p^4 - 30p^2 + 10) p^3 * (
Z  31       0.00000000 :  (21p^4 - 30p^2 + 10) p^3 * S
Z  32       0.00000000 :  (56p^6 - 105p^4 + 60p^2 - 1(
Z  33       0.00000000 :  (56p^6 - 105p^4 + 60p^2 - 1(
Z  34       0.00000000 :  (126 p^8 - 280p^6 + 210p^4 -
Z  35       0.00000000 :  (126 p^8 - 280p^6 + 210p^4 -
Z  36       0.00000000 :  (252p^10 - 630p^8 + 560p^6 -
```

c) If a field of 2° is introduced and the Zernike coefficients are calculated for the field point in the image and behind the 4th surface (the aplanatic), we get the following picture:

```
Surface                       : 4
Field                         : 2.0000 (deg)
Wavelength                    : 0.5000 µm
Peak to Valley (to chief)     :      0.42436528 waves
Peak to Valley (to centroid)  :      0.41949035 waves
RMS (to chief)                :      0.11961177 waves
RMS (to centroid)             :      0.11958708 waves
Variance                      :      0.01430107 waves squared
Strehl Ratio (Est)            :      0.56859687

RMS fit error                 :      0.00000000 waves
Maximum fit error             :      0.00000001 waves

Z   1       0.20794872 :  1
Z   2       0.00000000 :  (p) * COS (A)
Z   3       0.00490450 :  (p) * SIN (A)
Z   4       0.20837470 :  (2p^2 - 1)
Z   5      -0.00021696 :  (p^2) * COS (2A)
Z   6       0.00000000 :  (p^2) * SIN (2A)
Z   7       0.00000000 :  (3p^2 - 2) p * COS (A)
Z   8       0.00246706 :  (3p^2 - 2) p * SIN (A)
Z   9       0.00042809 :  (6p^4 - 6p^2 + 1)
Z  10       0.00000000 :  (p^3) * COS (3A)
Z  11      -0.00000102 :  (p^3) * SIN (3A)
Z  12      -0.00001191 :  (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       0.00000997 :  (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16       0.00000211 :  (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)
```

```
Surface                       : Image
Field                         : 2.0000 (deg)
Wavelength                    : 0.5000 µm
Peak to Valley (to chief)     :      0.98906306 waves
Peak to Valley (to centroid)  :      0.97834634 waves
RMS (to chief)                :      0.22880861 waves
RMS (to centroid)             :      0.22874623 waves
Variance                      :      0.05232484 waves squared
Strehl Ratio (Est)            :      0.12672931

RMS fit error                 :      0.00000000 waves
Maximum fit error             :      0.00000001 waves

Z   1       0.34701665 :  1
Z   2       0.00000000 :  (p) * COS (A)
Z   3       0.01078681 :  (p) * SIN (A)
Z   4       0.34699634 :  (2p^2 - 1)
Z   5      -0.27812765 :  (p^2) * COS (2A)
Z   6       0.00000000 :  (p^2) * SIN (2A)
Z   7       0.00000000 :  (3p^2 - 2) p * COS (A)
Z   8       0.00539378 :  (3p^2 - 2) p * SIN (A)
Z   9      -0.00001686 :  (6p^4 - 6p^2 + 1)
Z  10       0.00000000 :  (p^3) * COS (3A)
Z  11      -0.00140829 :  (p^3) * SIN (3A)
Z  12       0.00065752 :  (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       0.00000041 :  (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16       0.00000345 :  (20p^6 - 30p^4 + 12p^2 - 1)
Z  17       0.00000683 :  (p^4) * COS (4A)
Z  18       0.00000000 :  (p^4) * SIN (4A)
Z  19       0.00000000 :  (5p^2 - 4) p^3 * COS (3A)
```

In the image, defocus (which is here in field the field curvature) and astigmatism are the dominating aberrations. Directly behind the aplanatic surface, only defocus has a considerable amount. This shows, that the concentric surface limits the system performance by astigmatism and field curvature. The change in the coma of the aplanatic surface is extremly small.

3.3 Transverse aberration curve

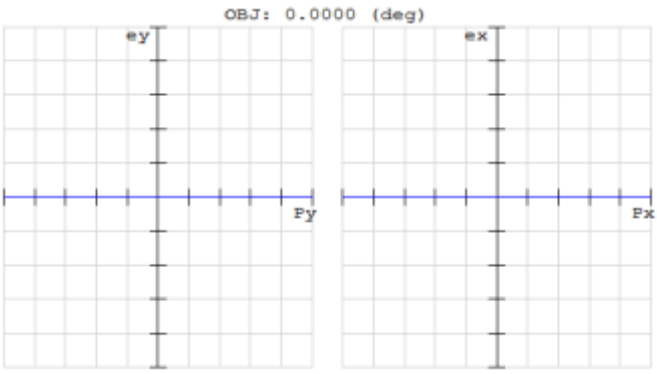
Establish a system with an ideal lens of focal length f = 100. mm, a wavelength of 600 nm and a collimated input bundle of diameter 10 mm.
a) Define the slider option with the image distance as a variable. Open the transverse aberration chart with a fixed scale of 100 μm. What happens with the aberration curve, if the slider is moved ?
b) Now introduce a thin glass plate in front of the perfect lens and define one side as a Zernike surface with coma as type (c8) of one wavelength. What is now the result for the moving slider ? Explain the result, if c7 is taken instead of c8.
c) If now spherical aberration is introduced by the plate in selecting c9, what is seen for the defocus ? Open also a spot diagram with fixed scale. Determine the best image plane for an overall small spot diameter ?

Solution:

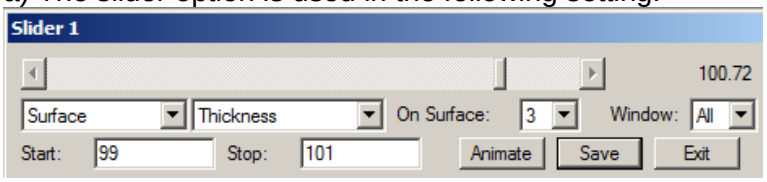
Setup of the initial system:

Lens Data Editor

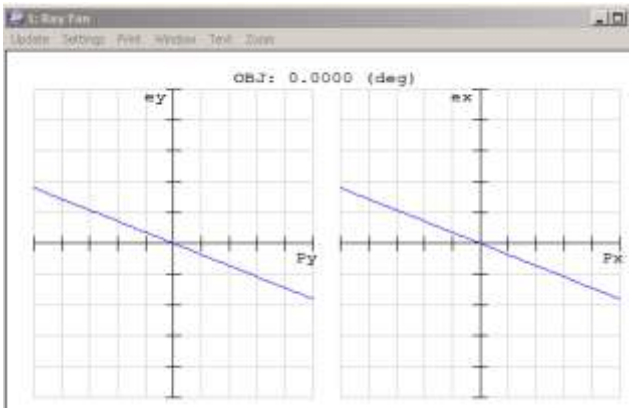
	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard		Infinity	Infinity		0.0000000	0.0000000		
1	Standard		Infinity	1.0000000		5.0000000	0.0000000		
STO	Paraxial			0.0000000		5.0000000			100.000000
3	Standard		Infinity	100.000000		5.0000000	0.0000000		
IMA	Standard		Infinity	-		0.0000000	0.0000000		



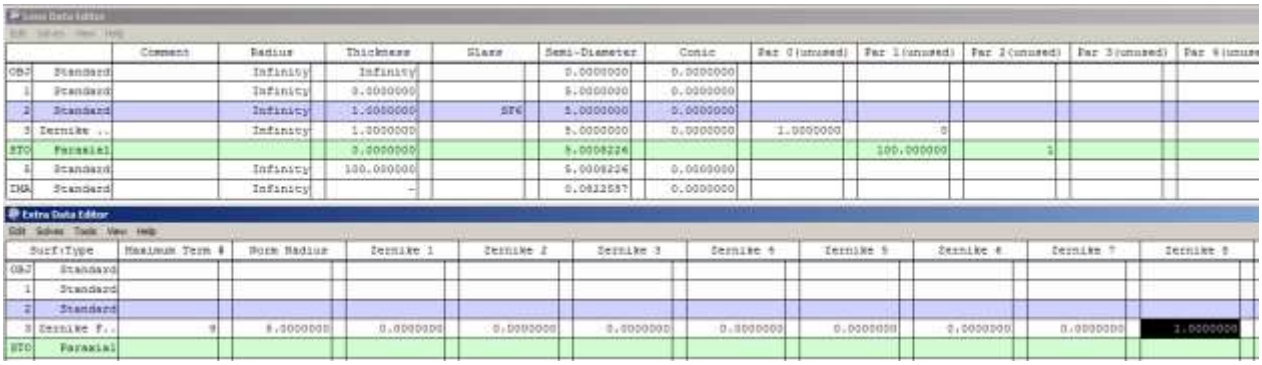
a) The slider option is used in the following setting:



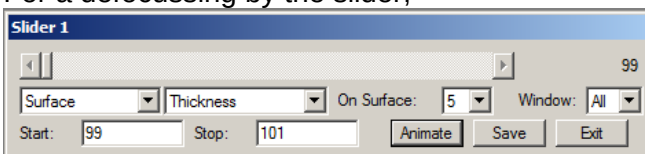
As a result, the transverse aberration curve is tilted corresponding to the interpretation of the transverse aberrations in the case of defocussing.



b) The system looks as follows:

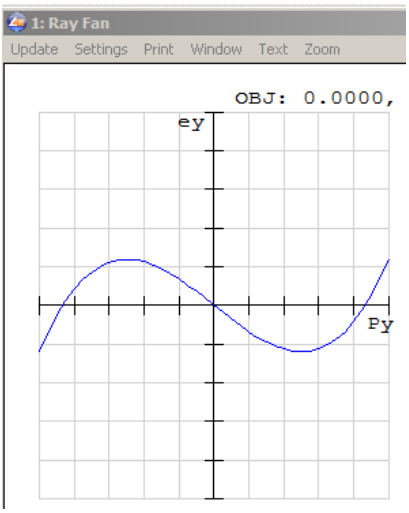


For a defocussing by the slider,



a strong parabolic shape due to the coma in the meridional plane is seen, which is tilted by the defocus.
If c7 is chosen the orintation of the coma is rotated and the parabola switches from the meridional to the sagittal plane.

c) For spherical aberration a cubic curve is superposed on the linear change. If the scale of the aberration curve is fixed to 300 μm, the best image plane is estimated to be at 101.44 mm. For this value, the residual zonal deviation has approximately the same size at the edge error.

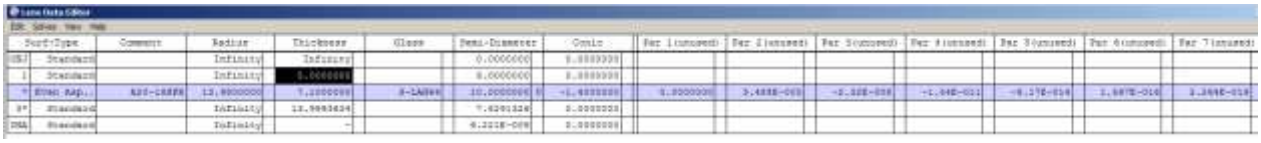


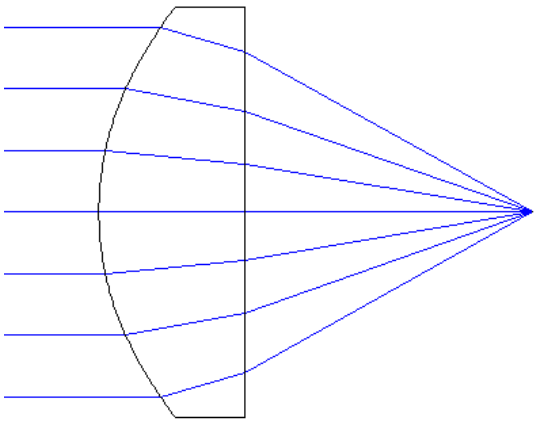
3.4 Aspherical lens

Load the catalof lens A20-18HPX form Asphericon.
a) What is the residual correction in wave aberrations and in spot size ?
b) Show, that the asphere is sensitive for finite field sizes by introducing a field with angle 0.1°. What is the dominating type of aberration ?
c) What is the highest order of the chosen Taylor expansion ? Calculate the performance on axis , if the three highest expansion coefficients are set to zero. Is the system still diffraction limited ?

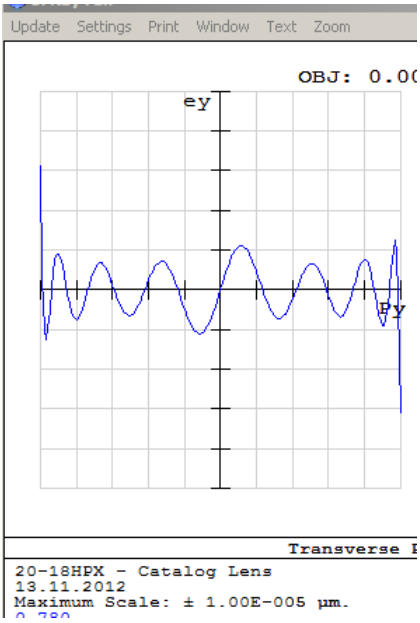
Solution:

The lens is established as follows:

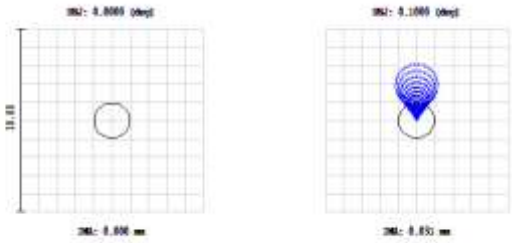




a) The Zernike coefficients are zero in the available accuracy. The plots of the residual transverse aberrations shows a maximum value of 1 nm.



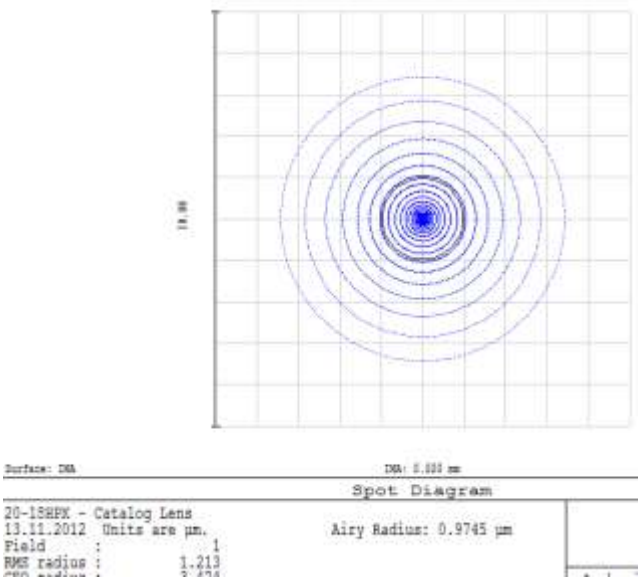
b) For the desired field, the spot shows coma in the range of the diffraction limit.



The Zernike expansion is domated by coma.

```
Field                       : 0.1000 (deg)
Wavelength                  : 0.7800 µm
Peak to Valley (to chief)   :     0.96880965 waves
Peak to Valley (to centroid) :     0.38180354 waves
RMS (to chief)              :     0.15898929 waves
RMS (to centroid)           :     0.06135497 waves
Variance                    :     0.00376443 waves squared
Strehl Ratio (Est)          :     0.86190189

RMS fit error               :     0.00000023 waves
Maximum fit error           :     0.00000112 waves

Z   1      0.00496625 :  1
Z   2      0.00000000 :  (p) * COS (A)
Z   3     -0.29390723 :  (p) * SIN (A)
Z   4      0.00493362 :  (2p^2 - 1)
Z   5     -0.00353074 :  (p^2) * COS (2A)
Z   6      0.00000000 :  (p^2) * SIN (2A)
Z   7      0.00000000 :  (3p^2 - 2) p * COS (A)
Z   8     -0.17306735 :  (3p^2 - 2) p * SIN (A)
Z   9     -0.00005601 :  (6p^4 - 6p^2 + 1)
Z  10      0.00000000 :  (p^3) * COS (3A)
Z  11     -0.00000114 :  (p^3) * SIN (3A)
Z  12      0.00011117 :  (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     -0.01747857 :  (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16     -0.00002371 :  (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      0.00000007 :  (5p^2 - 4) p^3 * SIN (3A)
```

c) If the 10th to the 14th order coefficients are set to zero the following data are obtained:




```
Wavelength                  : 0.7800 µm
Peak to Valley (to chief)   :     0.21375722 waves
Peak to Valley (to centroid) :     0.21375722 waves
RMS (to chief)              :     0.05444855 waves
RMS (to centroid)           :     0.05444855 waves
Variance                    :     0.00296464 waves squared
Strehl Ratio (Est)          :     0.88955007

RMS fit error               :     0.00000011 waves
Maximum fit error           :     0.00000056 waves

Z   1      0.03728090 :  1
Z   2      0.00000000 :  (p) * COS (A)
Z   3      0.00000000 :  (p) * SIN (A)
Z   4      0.07882151 :  (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      0.06361267 :  (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      0.02775550 :  (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)
```

With a Strehl niumber of 89% per definition the system is diffraction limited.