# Wave Aberrations and Zernike Coefficients

Load the system data from Moodle. It is a microscopic lens with high NA = 1.28 from the book of Laikin.

a) Show the rms wave aberrations as a function of the defocussing . Discuss the results

b) Show the rms wave aberration as a function of the field for all wavelengths. Is the system diffraction limited ?

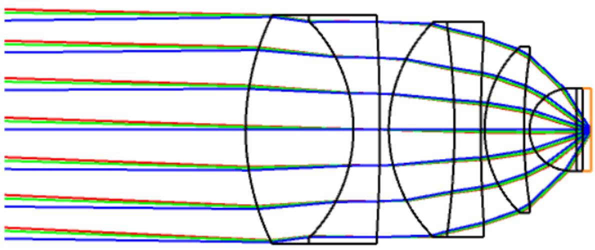
c) Calculate the Zernike coefficients for the primary wavelength on axis and for the maximum field size. What kind of aberration limits the performance in the field ?

d) Calculate the Zernikes on axis behind the first three components and in the image. What can be seen for the changes and the compensation effects in the spherical aberration coefficients ?

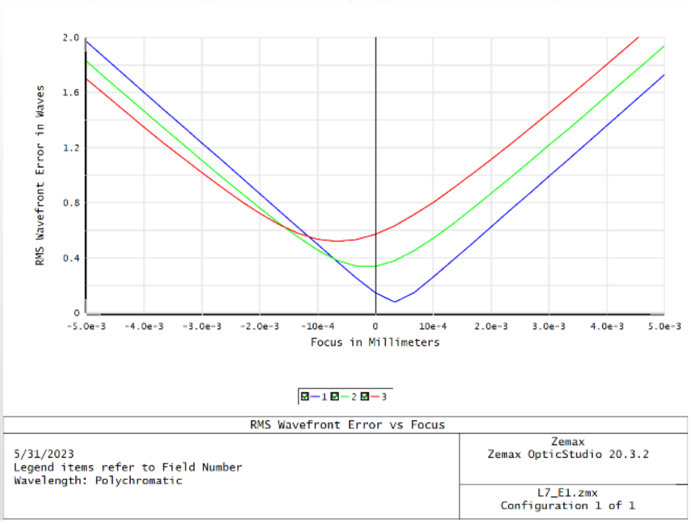
**Solution:**

The system data are as follows:

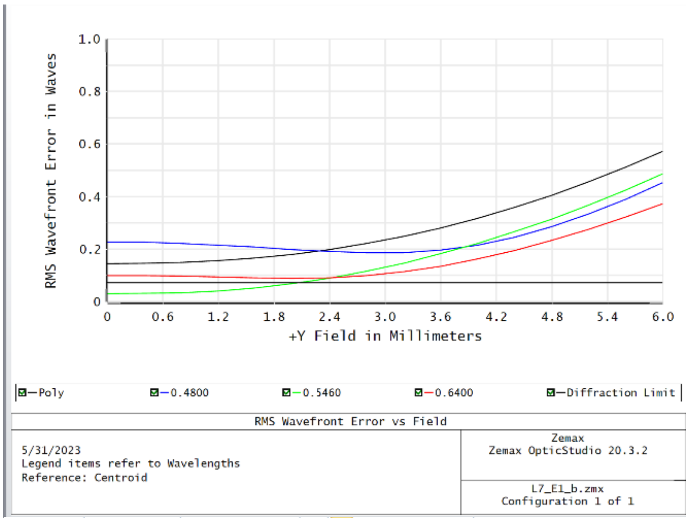
| | Surface Type | | Comment | Radius | Thickness | Material | Coating | Clear Semi-Dia |
|---|---|---|---|---|---|---|---|---|
| 0 | OBJECT | Standard ▾ | | Infinity | 167.867320 | | | 6.000000 |
| 1 | | Standard ▾ | | Infinity | 5.000000 | | | 2.477504 |
| 2 | | Standard ▾ | | 5.341620 | 2.232660 | CAF2 | | 2.361041 |
| 3 | | Standard ▾ | | -3.180080 | 0.548640 | F2 | | 2.239519 |
| 4 | STOP | Standard ▾ | | -38.305740 | 0.185420 | | | 2.220908 |
| 5 | | Standard ▾ | | 3.126740 | 1.358900 | CAF2 | | 2.217043 |
| 6 | | Standard ▾ | | -15.306040 | 0.546100 | F2 | | 2.136609 |
| 7 | | Standard ▾ | | 30.728920 | 0.078740 | | | 1.964774 |
| 8 | | Standard ▾ | | 2.372360 | 0.815340 | SK14 | | 1.713994 |
| 9 | | Standard ▾ | | 10.200640 | 0.115734 | | | 1.596243 |
| 10 | | Standard ▾ | | 0.853440 | 0.970280 | BK7 | | 0.852155 |
| 11 | | Standard ▾ | | Infinity | 0.128972 V | TYPEA | | 0.571722 |
| 12 | | Standard ▾ | | Infinity | 0.177800 | N-K5 | | 0.350250 |
| 13 | IMAGE | Standard ▾ | | Infinity | - | WATER | | 0.063182 |

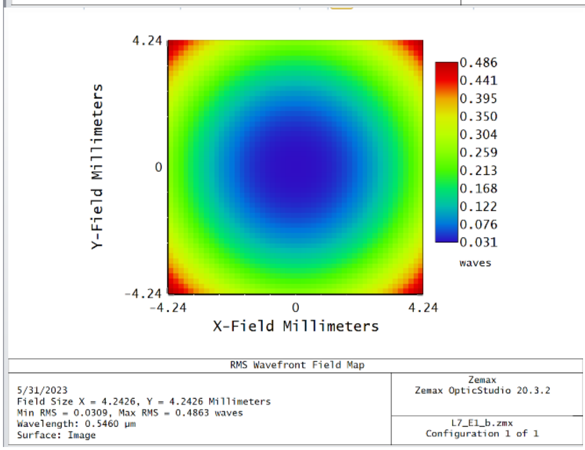


a) The Rms of the wave aberration as a function of the defocus is shown here for the 3 field points. It is seen, that the performance is decreasing for larger field points. Especially, also a shift in best image position is seen, which results from the lack of field flattening.




b) If the wave aberrations are plotted as a function of the field, it is seen, that the system is only diffraction limited in the green inside a field circle with radius 1.8 mm. The same can be seen in the field distribution of the rms for the primary wavelength.



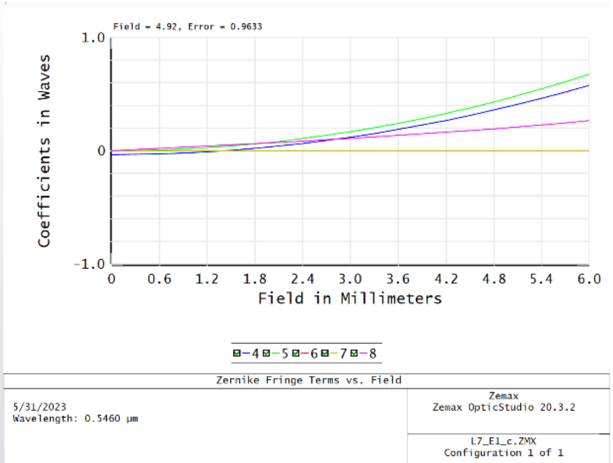




c) The Zernikes on axis and in the field also demonstrate the change of correction over the field size. In the field, the Marechal approximation for the Strehl ratio completely breaks down.

```
Surface                          :  Image
Field                            :  0.0000 mm
Wavelength                       :  0.5460 µm
Peak to Valley (to chief)        :      0.59580369 waves
Peak to Valley (to centroid)     :      0.59580369 waves
RMS (to chief)                   :      0.09103532 waves
RMS (to centroid)                :      0.09103532 waves
Variance                         :      0.00828743 waves squared
Strehl Ratio (Est)               :      0.72095786

RMS fit error                    :      0.00045823 waves
Maximum fit error                :      0.00229943 waves

Z   1      -0.16594574  :   1
Z   2       0.00000000  :   (p) * COS (A)
Z   3       0.00000000  :   (p) * SIN (A)
Z   4      -0.02585636  :   (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       0.12910795  :   (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       0.12255254  :   (20p^6 - 30p^4 + 12p^2 - 1)
Z  17      -0.00001223  :   (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       0.17460780  :   (70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)
Z  26       0.00000000  :   (p^5) * COS (5A)
Z  27       0.00000000  :   (p^5) * SIN (5A)
Z  28      -0.00001120  :   (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 * COS (3A)
Z  31       0.00000000  :   (21p^4 - 30p^2 + 10) p^3 * SIN (3A)
Z  32       0.00000000  :   (56p^6 - 105p^4 + 60p^2 - 10) p^2 * COS (2A)
Z  33       0.00000000  :   (56p^6 - 105p^4 + 60p^2 - 10) p^2 * SIN (2A)
Z  34       0.00000000  :   (126 p^8 - 280p^6 + 210p^4 - 60p^2 + 5) p * COS (A)
Z  35       0.00000000  :   (126 p^8 - 280p^6 + 210p^4 - 60p^2 + 5) p * SIN (A)
Z  36       0.05037324  :   (252p^10 - 630p^8 + 560p^6 - 210p^4 + 30p^2 - 1)
Z  37       0.01091366  :   (924p^12 - 2772p^10 + 3150p^8 - 1680p^6 + 420p^4 - 42p^2 + 1)
```

```
Surface                          :  Image
Field                            :  6.0000 mm
Wavelength                       :  0.5460 µm
Peak to Valley (to chief)        :      4.37741709 waves
Peak to Valley (to centroid)     :      2.78519800 waves
RMS (to chief)                   :      1.07370619 waves
RMS (to centroid)                :      0.47819760 waves
Variance                         :      0.22867294 waves squared
Strehl Ratio (Est)               :      0.00000000

RMS fit error                    :      0.00050678 waves
Maximum fit error                :      0.00328283 waves

Z   1       0.61332979  :   1
Z   2       0.00000000  :   (p) * COS (A)
Z   3       1.92417391  :   (p) * SIN (A)
Z   4       0.58266128  :   (2p^2 - 1)
Z   5       0.67929048  :   (p^2) * COS (2A)
Z   6       0.00000000  :   (p^2) * SIN (2A)
Z   7       0.00000000  :   (3p^2 - 2) p * COS (A)
Z   8       0.25054032  :   (3p^2 - 2) p * SIN (A)
Z   9      -0.04459339  :   (6p^4 - 6p^2 + 1)
Z  10       0.00000000  :   (p^3) * COS (3A)
Z  11      -0.04221907  :   (p^3) * SIN (3A)
Z  12       0.23084224  :   (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      -0.55294531  :   (10p^4 - 12p^2 + 3) p * SIN (A)
Z  16       0.12078918  :   (20p^6 - 30p^4 + 12p^2 - 1)
Z  17       0.00016941  :   (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       0.00180260  :   (5p^2 - 4) p^3 * SIN (3A)
Z  21       0.00639322  :   (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      -0.07231759  :   (35p^6 - 60p^4 + 30p^2 - 4) p * SIN (A)
Z  25       0.17579142  :   (70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)
Z  26       0.00000000  :   (p^5) * COS (5A)
Z  27      -0.00006555  :   (p^5) * SIN (5A)
Z  28       0.00067060  :   (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 * COS (3A)
Z  31       0.00263237  :   (21p^4 - 30p^2 + 10) p^3 * SIN (3A)
Z  32      -0.00152163  :   (56p^6 - 105p^4 + 60p^2 - 10) p^2 * COS (2A)
Z  33       0.00000000  :   (56p^6 - 105p^4 + 60p^2 - 10) p^2 * SIN (2A)
Z  34       0.00000000  :   (126 p^8 - 280p^6 + 210p^4 - 60p^2 + 5) p * COS (A)
Z  35      -0.01184470  :   (126 p^8 - 280p^6 + 210p^4 - 60p^2 + 5) p * SIN (A)
Z  36       0.05030055  :   (252p^10 - 630p^8 + 560p^6 - 210p^4 + 30p^2 - 1)
Z  37       0.01079007  :   (924p^12 - 2772p^10 + 3150p^8 - 1680p^6 + 420p^4 - 42p^2 + 1)
```

From the variation of the Zernikes over the field size it is seen, that a large tilt takes place. If only the primary aberrations are considered, Coma (c8), astigmatism (c5) and field curvature (c4) are approximately of the same size.



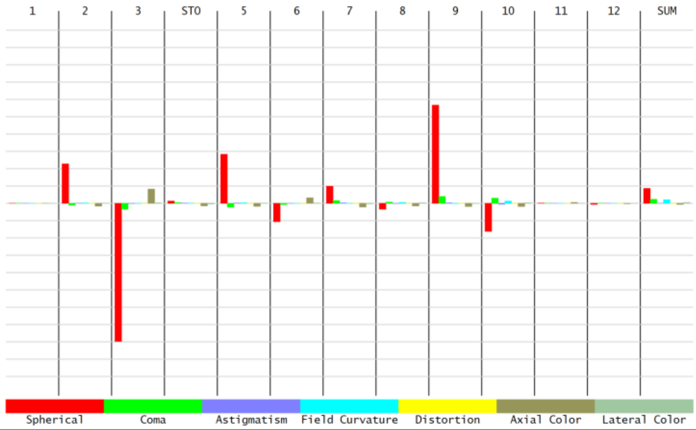

d) If the Zernikes are calculated for thesurface indices 4, 7 and 9 and the image, we get the following data:

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Z | 1 | -16.44721392 | Z | 1 | -9.33855398 | Z | 1 | 5.38758877 | Z | 1 | -0.16594574 | : | 1 |
| Z | 2 | 0.00000000 | Z | 2 | 0.00000000 | Z | 2 | 0.00000000 | Z | 2 | 0.00000000 | : | (p) * COS (A) |
| Z | 3 | 0.00000000 | Z | 3 | 0.00000000 | Z | 3 | 0.00000000 | Z | 3 | 0.00000000 | : | (p) * SIN (A) |
| Z | 4 | -26.12095807 | Z | 4 | -15.10166076 | Z | 4 | 8.31509634 | Z | 4 | -0.02585636 | : | (2p^2 - 1) |
| Z | 5 | 0.00000000 | Z | 5 | 0.00000000 | Z | 5 | 0.00000000 | Z | 5 | 0.00000000 | : | (p^2) * COS (2A) |
| Z | 6 | 0.00000000 | Z | 6 | 0.00000000 | Z | 6 | 0.00000000 | Z | 6 | 0.00000000 | : | (p^2) * SIN (2A) |
| Z | 7 | 0.00000000 | Z | 7 | 0.00000000 | Z | 7 | 0.00000000 | Z | 7 | 0.00000000 | : | (3p^2 - 2) p * COS (A) |
| Z | 8 | 0.00000000 | Z | 8 | 0.00000000 | Z | 8 | 0.00000000 | Z | 8 | 0.00000000 | : | (3p^2 - 2) p * SIN (A) |
| Z | 9 | -10.74084716 | Z | 9 | -6.56724253 | Z | 9 | 3.29615815 | Z | 9 | 0.12910795 | : | (6p^4 - 6p^2 + 1) |

It is seen, that the contributions of the various components compensate the effect of the c9. The contributions are approximately (subtracting the absolute values):

-10.74 (surfaces 2,3,4) , +4.18 (surfaces 5,6,7) ,, +9.86 (surfaces 8,9) , -3.16 (surfaces 10,11,12)

If the Seidel contributions are inspected, qualitatively the same result occurs. It is seen in the Zernike table, that also a considerable contribution of 5[th] order spherical aberrations should be compensated.




Seidel Diagram

5/31/2023
Wavelength: 0.5460 µm.
Maximum aberration scale is 0.20000 Millimeters.
Grid lines are spaced 0.02000 Millimeters.

Zemax
Zemax OpticStudio 20.3.2

L7_E1_c.ZMX
Configuration 1 of 1

## 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.

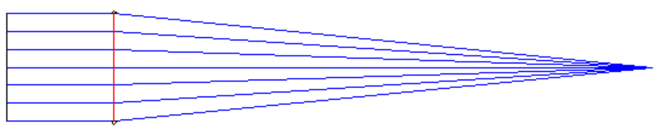
c) Aplanatic means, that the linear coma vanishes and the imaging is free of coma for a small but finite field size. Show this property by using a small field of 2° for the current system. What is the largest present aberration ?

**Solution:**

The initial focussing lens is established as follows:

Lens Data Editor
Edit Solves View Help

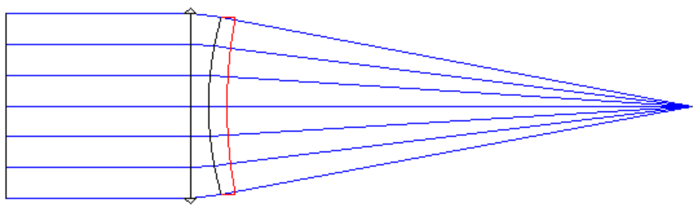
| | | Comment | Radius | Thickness | Glass | Semi-Diameter | Conic | Par 0 (unused) | Par 1 (unused) |
|---|---|---|---|---|---|---|---|---|---|
| OBJ | Standard | | Infinity | Infinity | | 0.0000000 | 0.0000000 | | |
| 1 | Standard | | Infinity | 10.0000000 | | 5.0000000 | 0.0000000 | | |
| STO | Paraxial | | | 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 behind the lens. The first surface is made aplanatic by a solve, the second surface is mad concentric by choosing the solve 'marginal ray normal' to force the marginal ray to be concentric.

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 | N | 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. It can also be seen, that the marginal ray is concentric at the surface 5.

```
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  5.0000000000E+000  0.0000000000E+000   0.0000000000   0.0000000000
  2   0.0000000000E+000  5.0000000000E+000  0.0000000000E+000   0.0000000000  -0.0995037190
  3   0.0000000000E+000  5.0000000000E+000  0.0000000000E+000   0.0000000000  -0.0995037190
  4   0.0000000000E+000  4.8303110655E+000  6.9688934549E-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 :
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 *
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      0.00065732 :  (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 extremely small.