

# **Simulation of Zernike Aberrations in optical systems**

**Michael Koch, [astroelectronic@t-online.de](mailto:astroelectronic@t-online.de)**

**July 5, 2018**

This paper is about three related questions:

1. In a Newton telescope we have two mirrors. It's well known how the primary mirror's Zernike aberrations look like in the focal plane. But what about the Zernike aberrations of the secondary mirror? Let's assume we compare two telescopes: Telescope 1 has one wave of astigmatism in the primary mirror, and a perfect secondary. Telescope 2 has a perfect primary, and one wave of astigmatism in the secondary. Let's assume we don't re-focus. Will we see the same aberrations in the focal plane in both cases, or can we argue that the secondary mirror's aberrations are less severe because they originate nearer to the focal plane?
2. Using very fast f/2.6 to f/3.0 Newton telescopes it was observed that significant spherical aberration was visible in the star test. However the primary mirror was found to be near-perfect, confirmed by two independent interferometric tests. It seems the spherical aberration is produced by the eyepiece, and different eyepiece types can produce over- or undercorrection. The eyepieces can be tested with a Zygo Fizeau interferometer at the same f/ratio as in the telescope. Now let's assume we compare two telescopes: Telescope 1 has one wave of spherical aberration in the primary mirror, and a perfect eyepiece. Telescope 2 has a perfect primary, and one wave of spherical aberration in the eyepiece. Let's assume we don't re-focus. Will we see the same aberrations in the focal plane in both cases, or can we argue that the eyepiece's aberrations are less severe because they originate nearer to the focal plane? Additional question: Does it matter where in the eyepiece the aberration originates, near the field lens or near the eye lens?
3. If we install a plane window in front of the telescope, and if this window produces aberrations, will the visible aberrations in the focal plane depend on the distance of the window in front of the telescope?

I asked these questions to a few people and got different answers. So I decided to make some simulations with BEAM4 software, which can be downloaded here:

<https://www.stellarsoftware.com/>

The simulated telescope is a Newton telescope with 100mm diameter and 1000mm focal length. It has a single-lens eyepiece and the system does also include a single-lens eye. The radii and conic constants of the lenses were optimized for best on-axis performance, much better than diffraction-limited. The index of refraction is a constant, which means we are using monochromatic light. The light source emits a parallel on-axis beam of light, like in a star test. Additionally there are 6 thin glass windows in the telescope. They are used to insert Zernike aberrations at different places along the optical path. The first two windows are 2m and 1m in front of the primary, the 3rd is a few Millimeters in front of the primary (it's only used for incoming light, not for reflected light), the 4th is halfway between the primary and the focal plane, the 5th is just in front of the secondary, and the 6th is between the eyepiece lens and the eyepiece, at the position where glasses would be. The diameters of all windows were chosen to be identical to the beam's diameter at that position, or a few percent larger. It's also possible to apply Zernike aberrations to one surface of the two lenses. In total we have 8 places along the optical path where Zernike aberrations can be added. I didn't want to add the aberrations directly to the mirror surfaces, because the wavefront error is twice the surface error. All places where aberrations can be added are air/glass boundaries and in all cases the index of refraction is 1.55. That means if the Zernike coefficient is set to 0.001mm, the wavefront error is  $(1.55 - 1.00) * 0.001\text{mm} = 550\text{nm}$ , which is one wave of green light.

This is the optics file:

```

19 surfaces
Dia  Index  Pitch  X      Z      Curv      Asph      Zern4      Mir
-----:-----:-----:-----:-----:-----:-----:-----:-----:-----
100 :      :      : -1001 :      :      : 0.000 : lens : Window1
100 : 1.55 :      : -1000 :      :      :      : lens : Window1
100 :      :      : 0 :      :      : 0.000 : lens : Window2
100 : 1.55 :      : 1 :      :      :      : lens : Window2
100 :      :      : 998 :      :      : 0.000 : lens : Window3
100 : 1.55 :      : 999 :      :      :      : lens : Window3
100 :      :      : 1000 : -0.00050 : -1.0000 :      : mir  : PrimaryMirror
50 :      :      : 495 :      :      : 0.000 : lens : Window4
50 : 1.55 :      : 494 :      :      :      : lens : Window4
12 :      :      : 115 :      :      : 0.000 : lens : Window5
12 : 1.55 :      : 114 :      :      :      : lens : Window5
30 :      : 45 :      : 100 :      :      :      : mir  : SecondaryMirror
3.2 :      : 90 : 130 : 100 : -0.00151 :      : 0.000 : lens : EyepieceLens
3.2 : 1.55 : 90 : 131 : 100 : -0.07539 : -1.3481 :      : lens : EyepieceLens
3.2 :      : 90 : 140 : 100 :      :      : 0.000 : lens : Window6
3.2 : 1.55 : 90 : 141 : 100 :      :      :      : lens : Window6
3.2 :      : 90 : 149 : 100 : 0.06438 : 1.5216 :      : lens : EyeLens
3.2 : 1.55 : 90 : 150 : 100 : 0.02123 :      : 0.000 : lens : EyeLens
20 :      : 90 : 180 : 100 :      :      :      : final : Retina

```

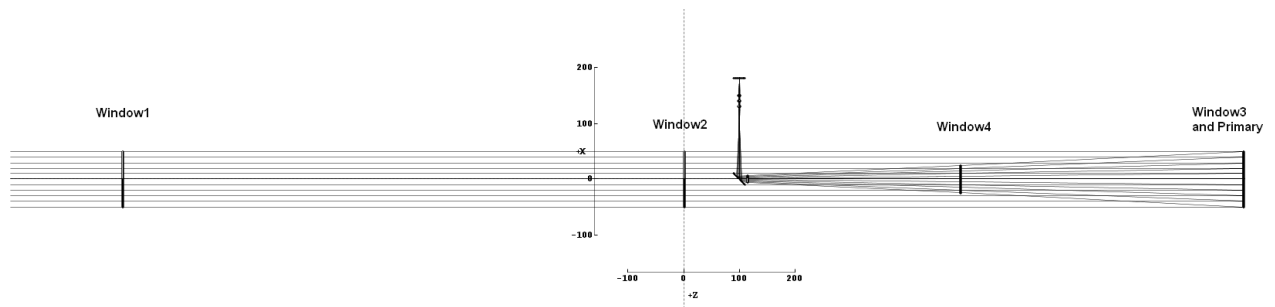
This is the ray file:

```

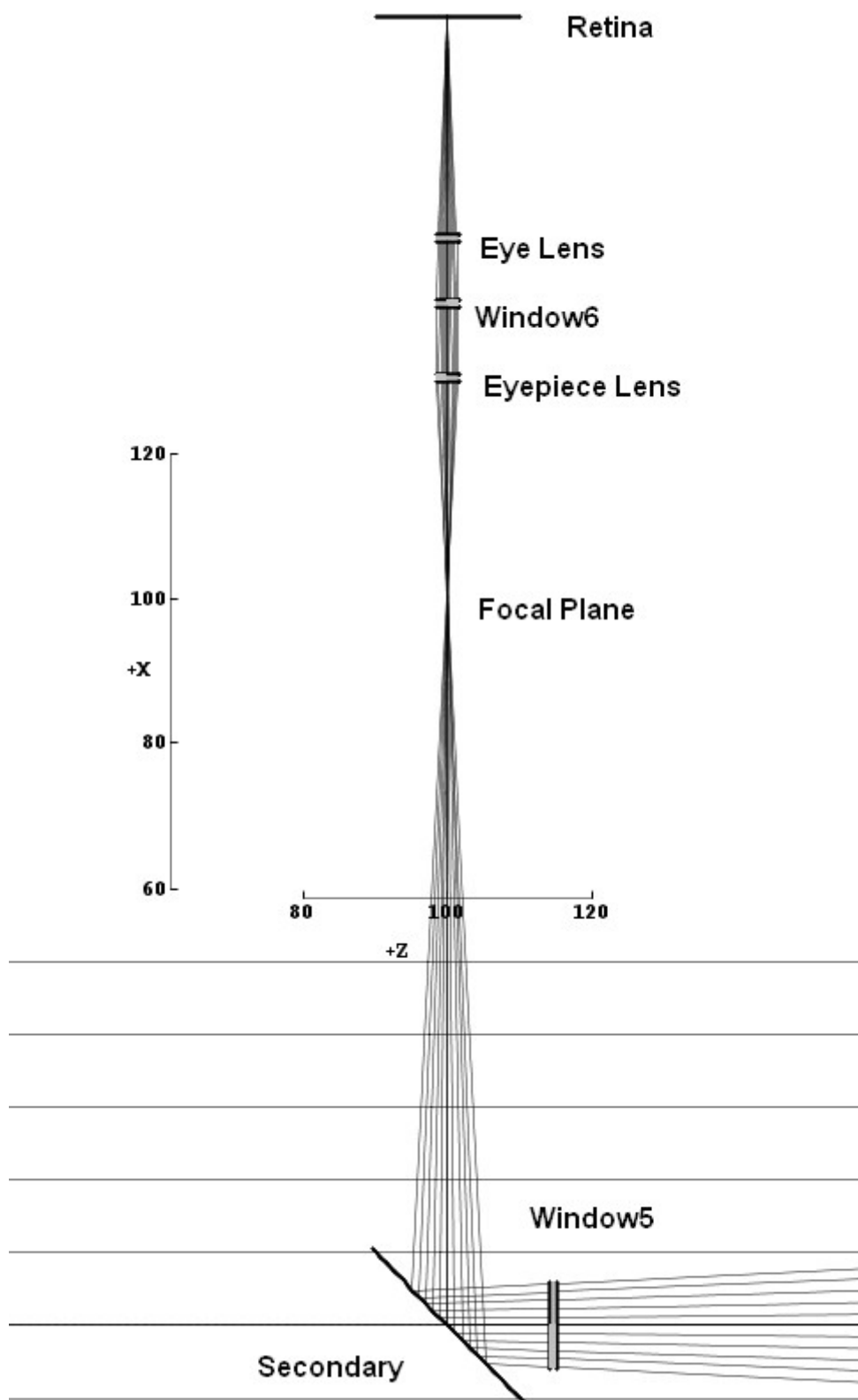
13 rays
X0  Y0  Z0      xgoal  ygoal  xfinal      yfinal      NOTES
-----:-----:-----:-----:-----:-----:-----:-----:-----
-50:  0:-1200 :  0 :  0 :  -0.000001:  0.000000:OK17 :
-40:  0:-1200 :  0 :  0 :   0.000011:  0.000000:OK17 :
-30:  0:-1200 :  0 :  0 : -0.000006:  0.000000:OK17 :
-20:  0:-1200 :  0 :  0 : -0.000018:  0.000000:OK17 :
-10:  0:-1200 :  0 :  0 : -0.000015:  0.000000:OK17 :
  0:  0:-1200 :  0 :  0 :   0.000000:  0.000000:OK17 :
 10:  0:-1200 :  0 :  0 :   0.000015:  0.000000:OK17 :
 20:  0:-1200 :  0 :  0 :   0.000018:  0.000000:OK17 :
 30:  0:-1200 :  0 :  0 :   0.000006:  0.000000:OK17 :
 40:  0:-1200 :  0 :  0 : -0.000011:  0.000000:OK17 :
 50:  0:-1200 :  0 :  0 :   0.000001:  0.000000:OK17 :
  0: -50:-1200 :  0 :  0 :   0.000000: -0.000001:OK17 :
  0:  50:-1200 :  0 :  0 :   0.000000:  0.000001:OK17 :

```

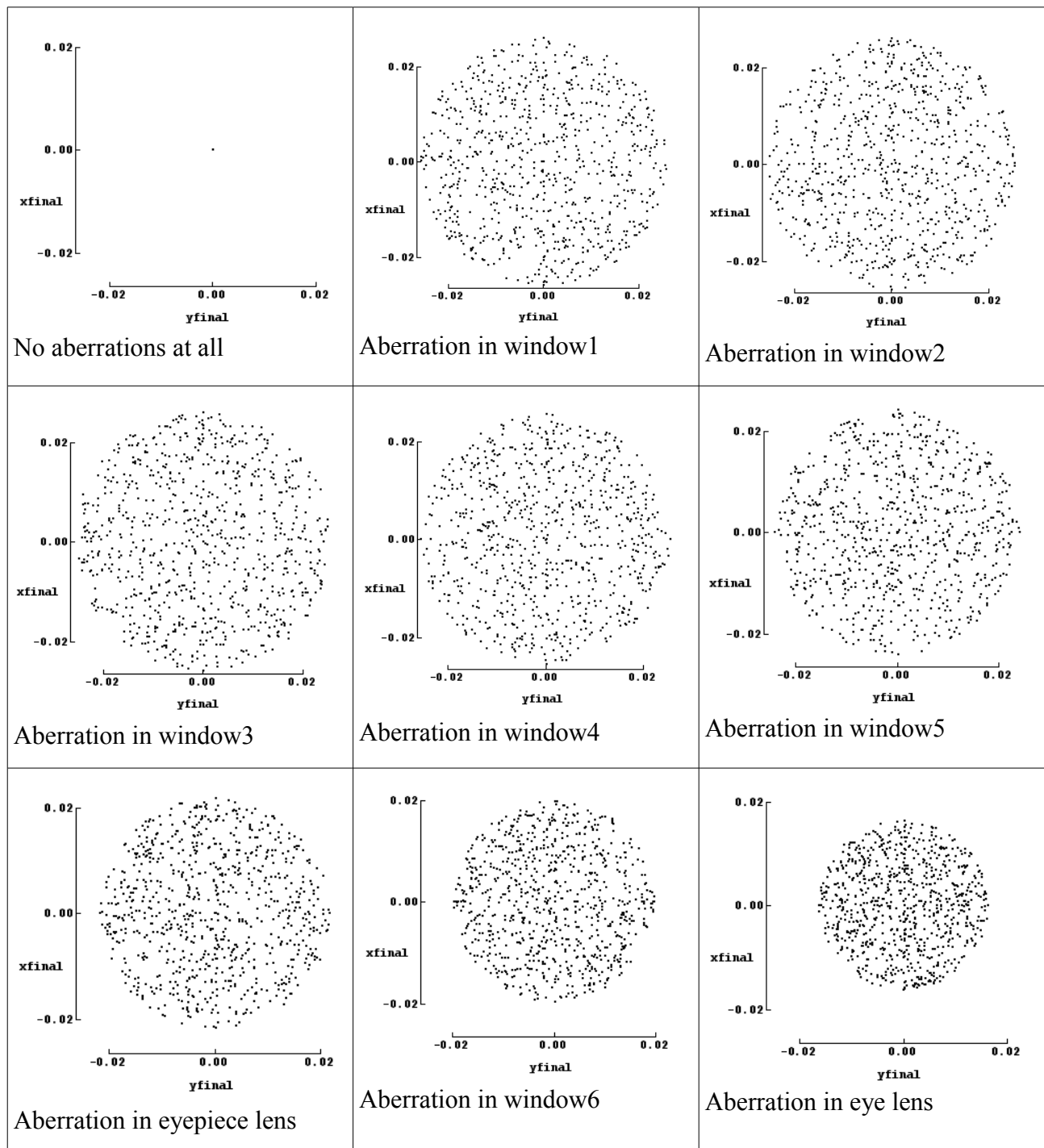
This is the optical layout:



This is an enlargement of the secondary / eyepiece / eye section:



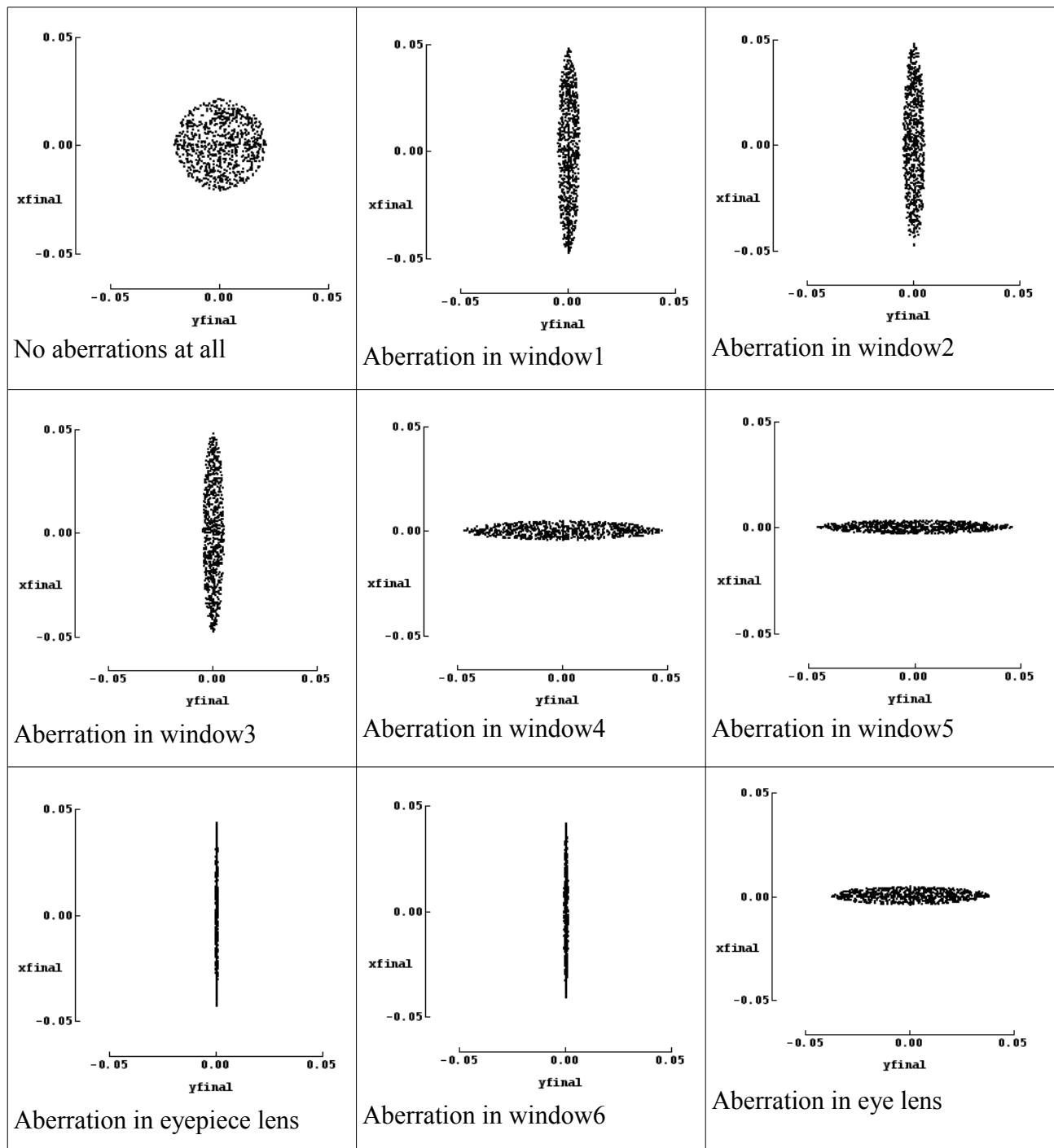
I did set one of the 8 values in the „Zern4“ column to 0.001 and leave the all other at 0.000. Plotted are 1000 random rays in the final retina plane.



The result is interesting: The visible aberration in the retina plane doesn't depend on the position where the aberration is applied.

The diameters of the last two plots are a little bit smaller than the other. But there's an easy explanation for this: The diameter of window6 and the eye lens are a few percent larger than the beam diameter at these positions. It's clearly visible when you zoom in.

This is the same simulation with a 0.5mm defocue. I did move the retina to  $x = 180.5\text{mm}$ . Please note the scale bars have changed as well.

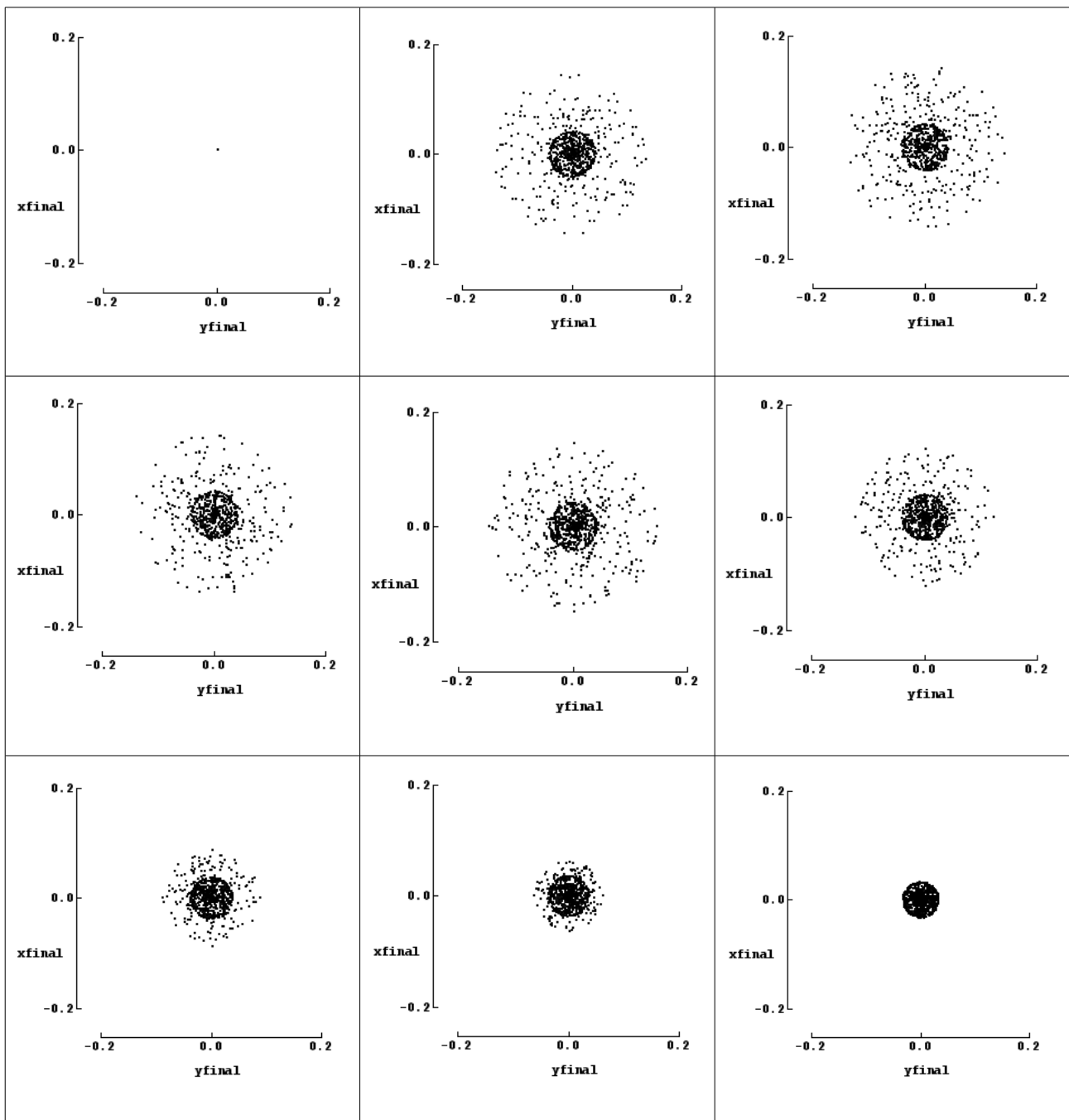


Why are some of the ellipses rotated 90°? Not completely understood, may be because the light is travelling in  $-Z$  direction? It seems the sign of the Zernike polynomial gets inverted somehow.

Why are the ellipses narrower, if the aberration is applied to the eyepiece lens or window6?

I don't know.

This is the same simulation with one wave of spherical aberration. No defocus. I did change „Zern4“ to „Zern8“ in the headline of the optics file.



The result is the same as before: The visible aberration in the retina plane doesn't depend on the position where the aberration is applied. I should have made the diameters of the last lenses a little bit smaller. Then all diagrams would look the same.