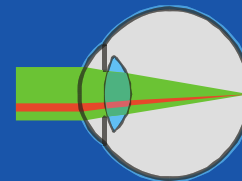


About the optics of the eye

Peter Unsbo

Kungliga Tekniska Högskolan



Biomedical and x-ray physics
Visual Optics

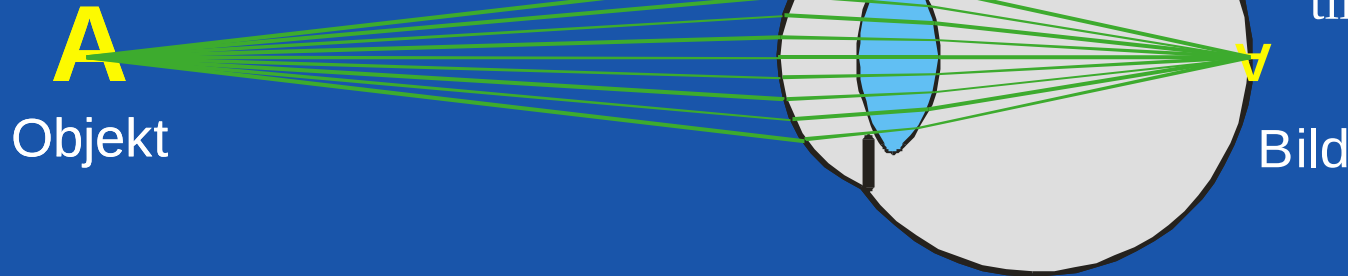
Innehåll

- Optiska begränsningar i ögat
- Hur mäter man ögats aberrationer?
- Hur skriver man vågfrontsrecept?
- Hur påverkas synen?
- Aberrationskorrektur? Supersyn?

Synprocessen

1. Avbildning

Ögats optik ger en bild av det man tittar på på näthinnan.



2. Sampling

Näthinnans receptorer läser av bilden och skickar informationen till hjärnan.

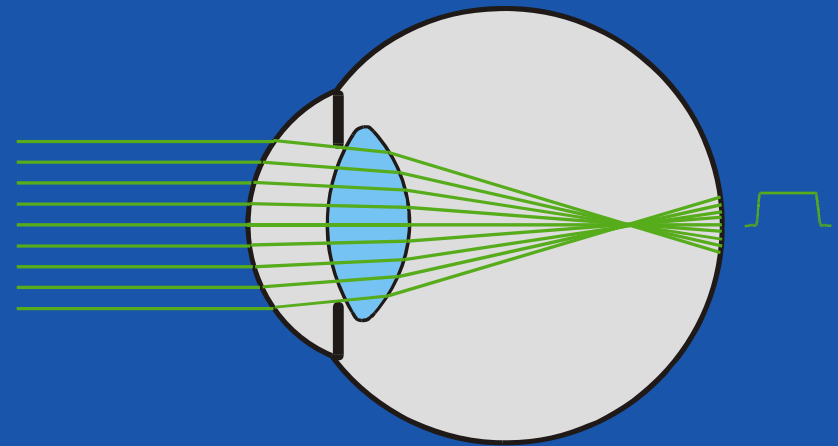
3. Perception

Informationen bearbetas i syncentrum i hjärnan

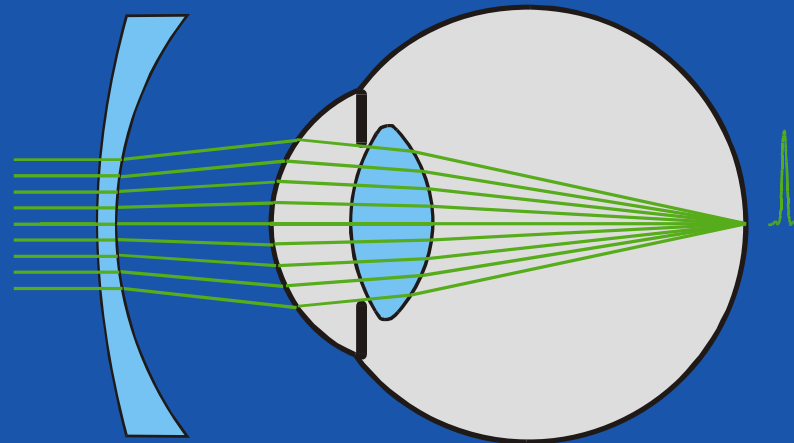
Ögats optiska begränsningar

- Defokusering
- Aberrationer
- Diffraktion
- Spridning

Brytningsfel



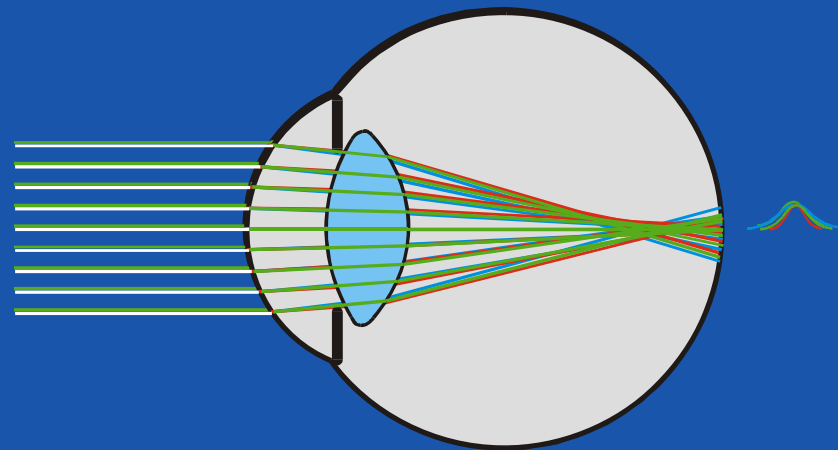
Korrigerat öga



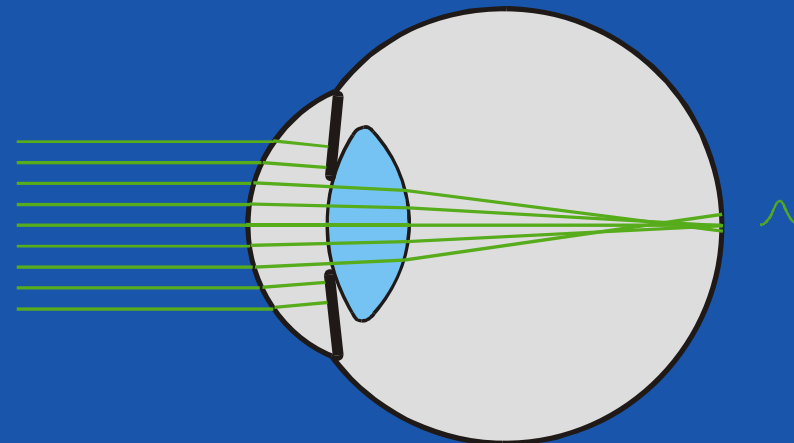
Ögats optiska begränsningar

- Defokusering
- Aberrationer
 - Monokromatiska
 - Kromatiska
- Diffraktion
- Spridning

Aberrationer

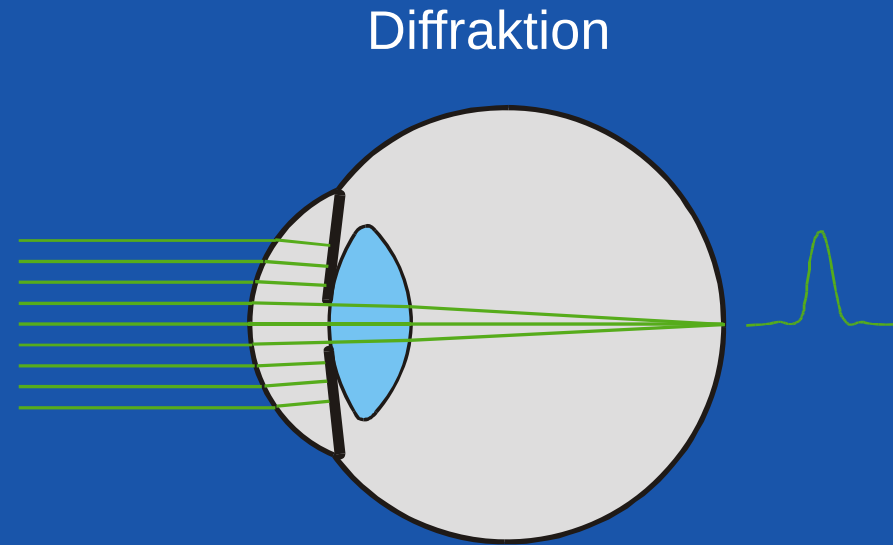


Aberrationer



Ögats optiska begränsningar

- Defokusering
- Aberrationer
- Diffraction**
- Spridning



Ögats optiska begränsningar

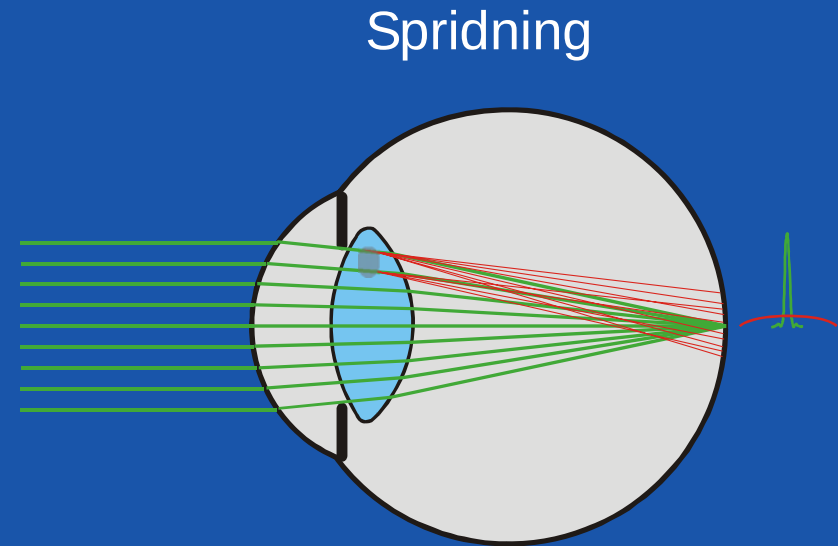
- Defokusering
- Aberrationer
- Diffraktion
- Spridning (PSF $> 1^\circ$)

Cornea 30%, $\sim 1/\lambda^4$

Lins 40%

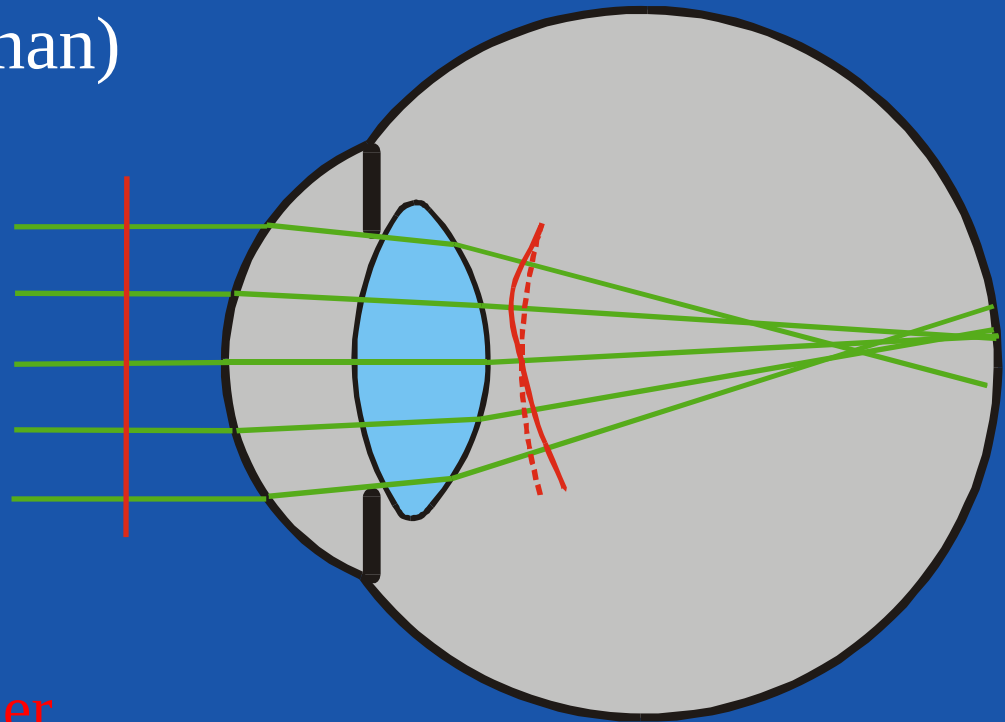
Iris 5%

Retina 25%



Hur ger man ett mått på ögats aberrationer?

- I Bildplanet (nätinnan)
 - PSF
 - MTF
- I Pupillplanet
 - Strålarnas avvikelse
 - Vågfrontsaberrationer



Vågfrontsaberrationer

Svårt att mäta
inne i ögat!

Vänd på ljuset!

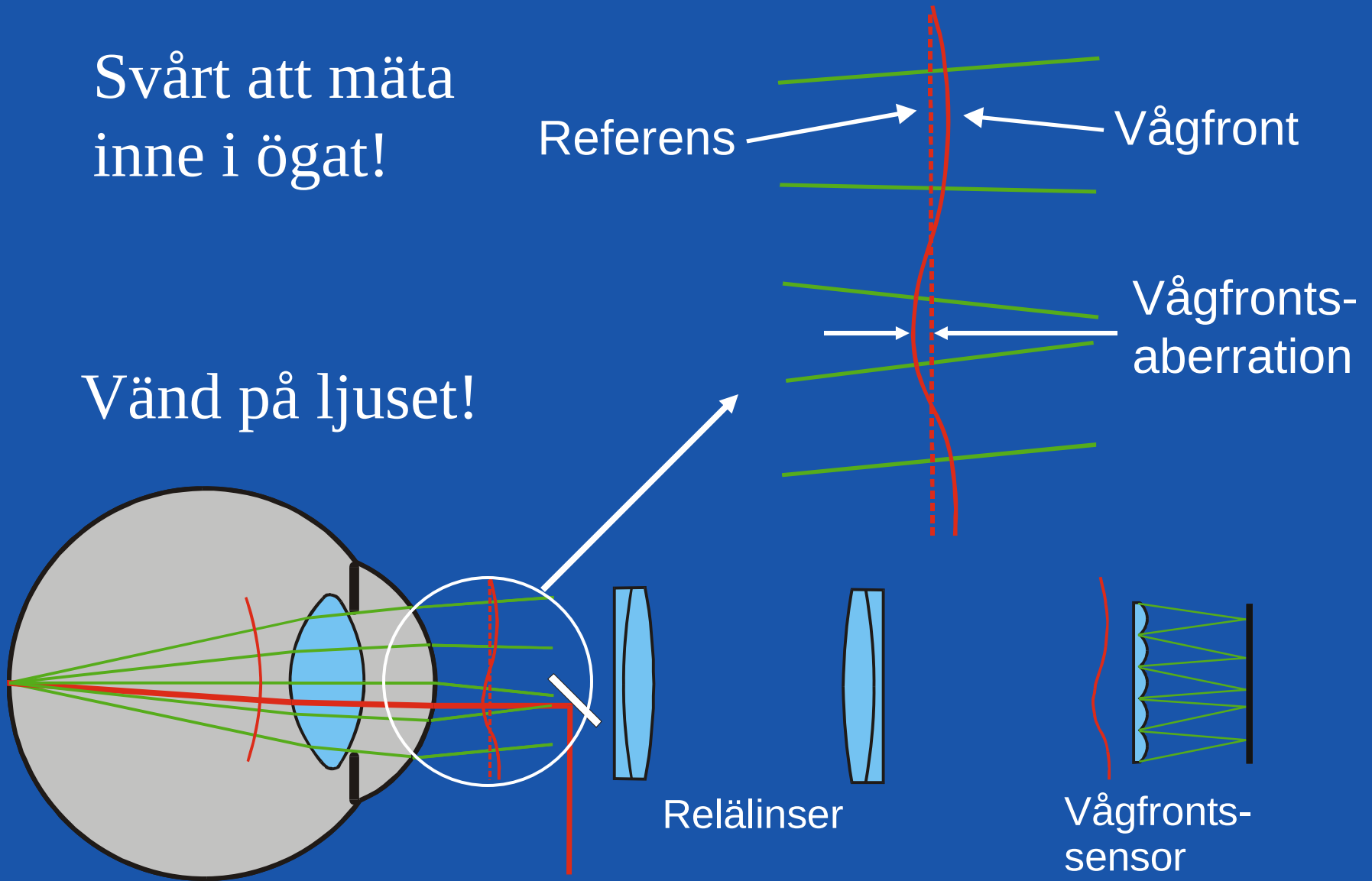
Referens

Vågfront

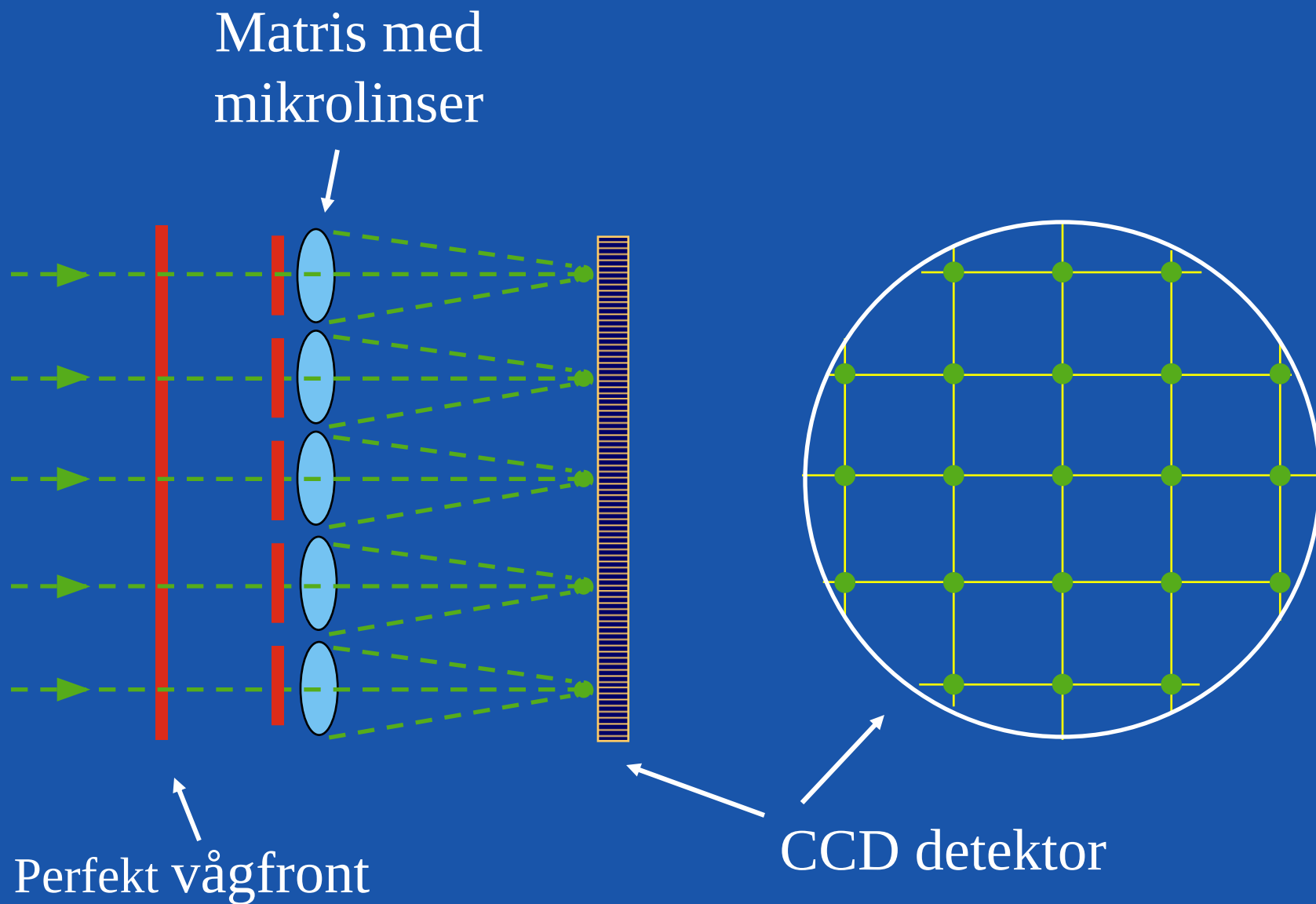
Vågfronts-
aberration

Relälinser

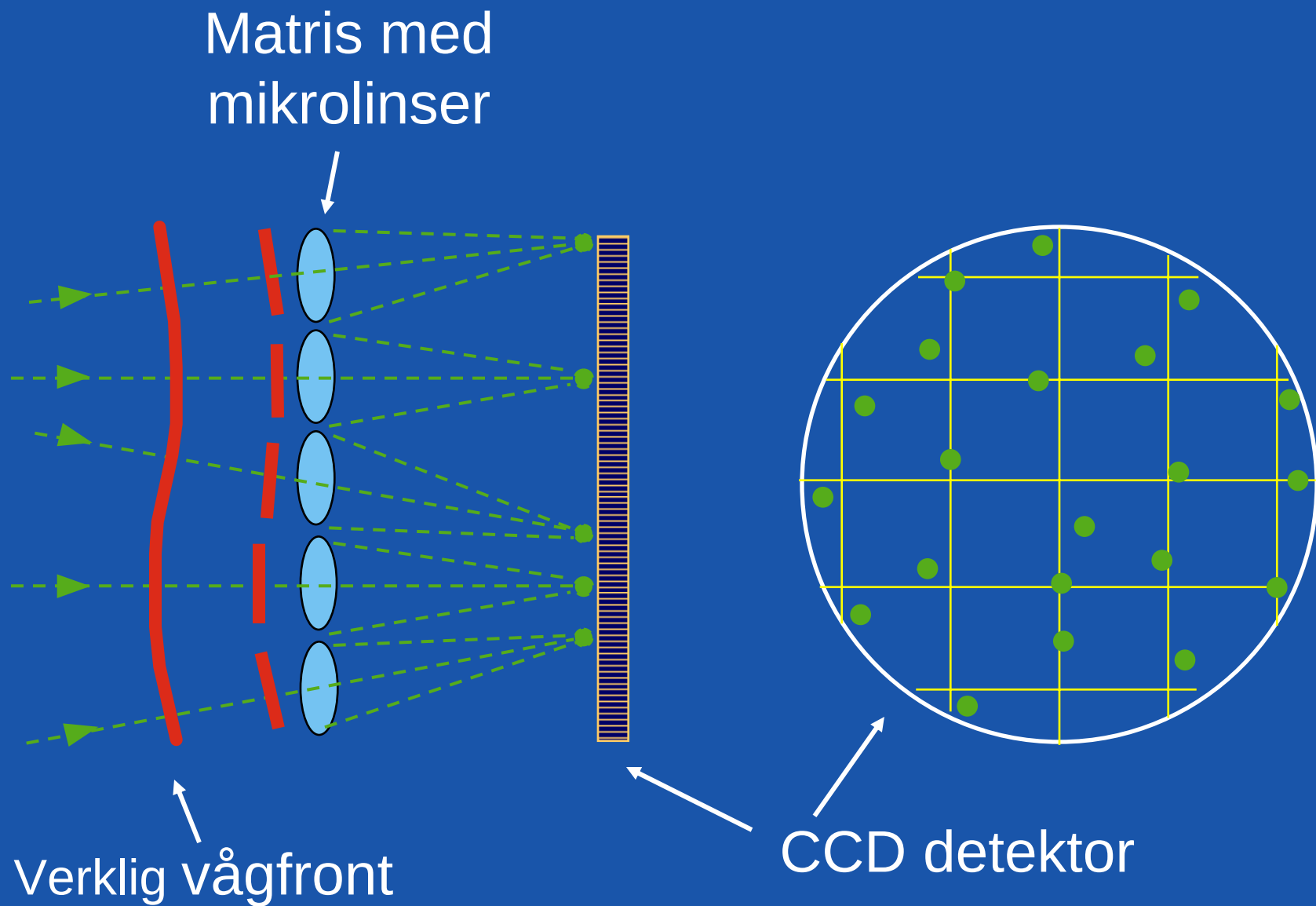
Vågfronts-
sensor



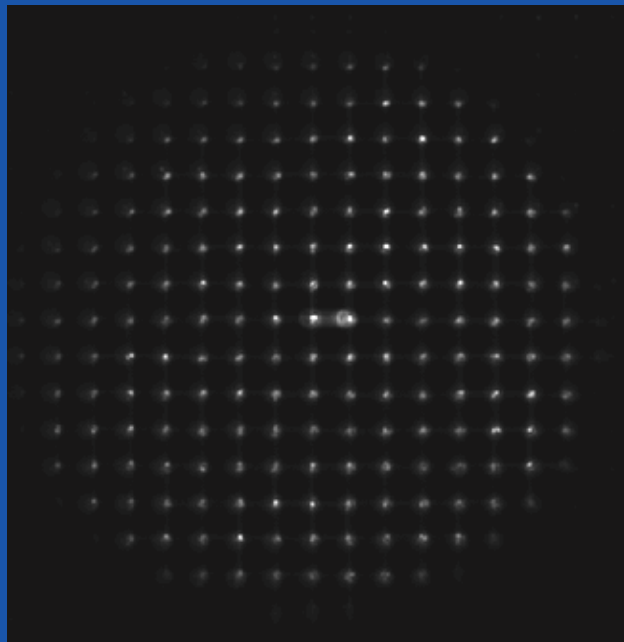
Hartmann-Shack sensorn



Hartmann-Shack sensorn



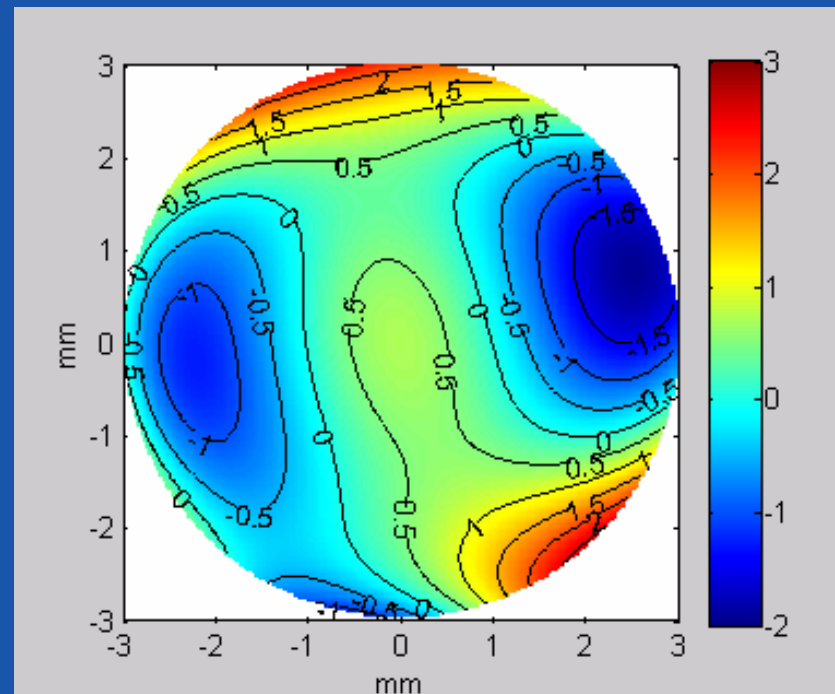
Hartmann-Shack sensorn



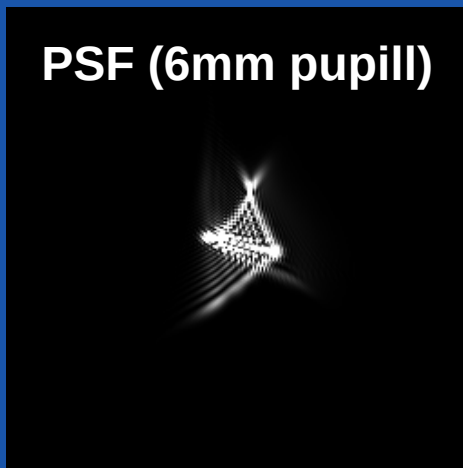
CCD-detektorns
bild



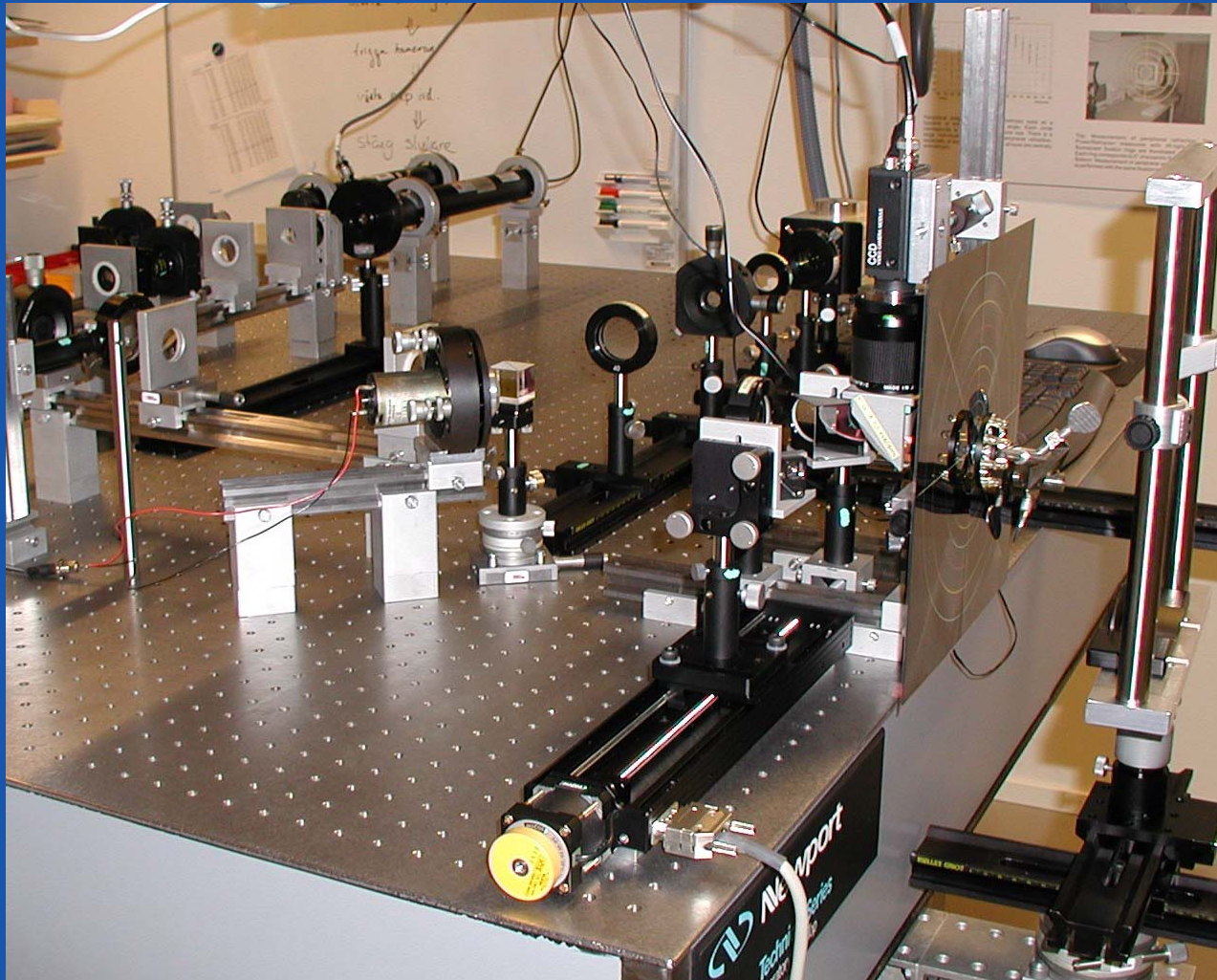
Vågfrontskarta
(höjd i mikrometer)



PSF (6mm pupill)

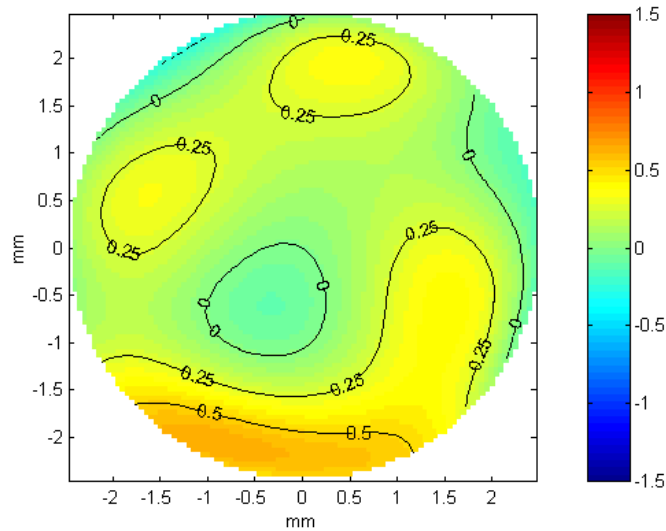


Hartmann-Schack sensorn

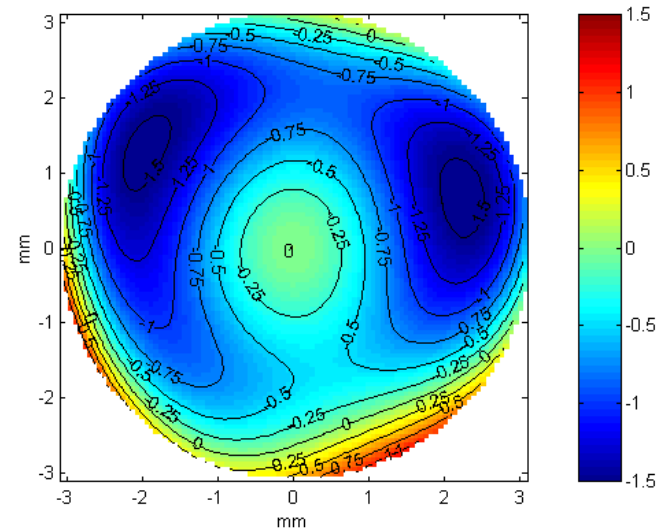


Exempel på vågfrontsaberrationer

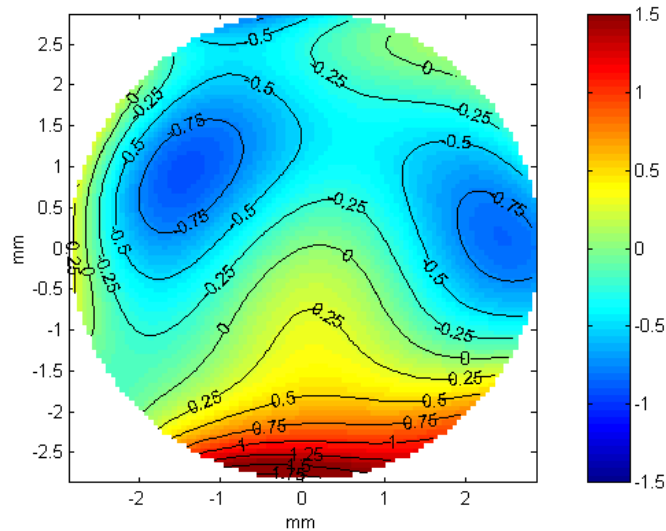
H



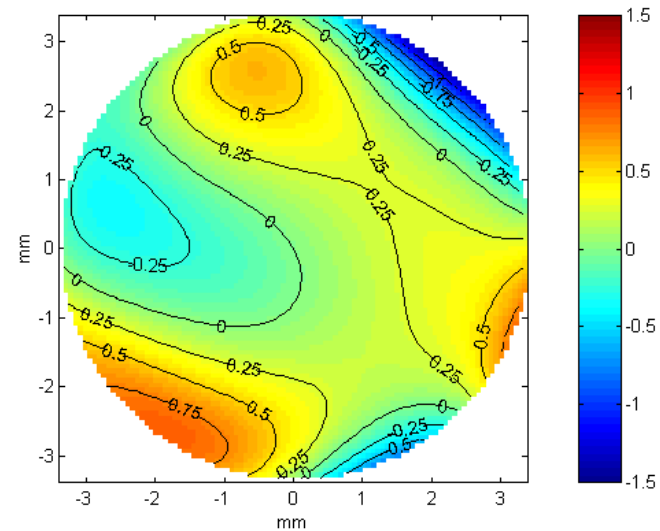
L



J



S



Zernikepolynom

Uppsättning standardvågfronter

$$Z_n^m(\rho, \theta) = N(\rho^n + \dots) \times \begin{cases} \cos(m\theta) \\ \sin(m\theta) \end{cases}$$



Zernike-
polynom



Radiellt
polynom

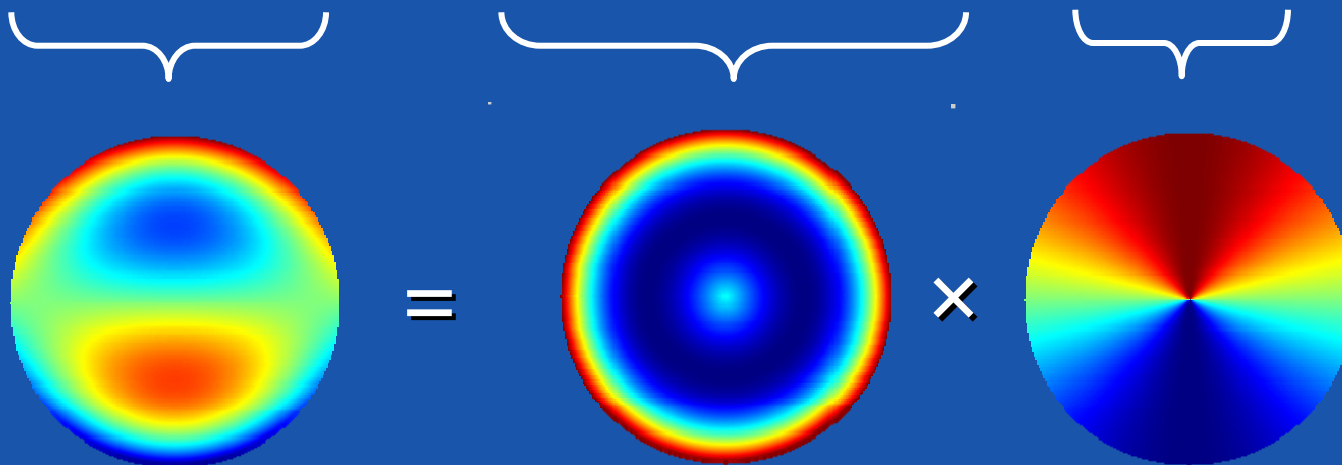


Vinkel-
funktion

Zernikepolynom

Exempel: Z_3^{-1} (Vertikal koma)

$$Z_3^{-1}(\rho, \theta) = \sqrt{8}(3\rho^2 - 2\rho) \times \sin(\theta)$$



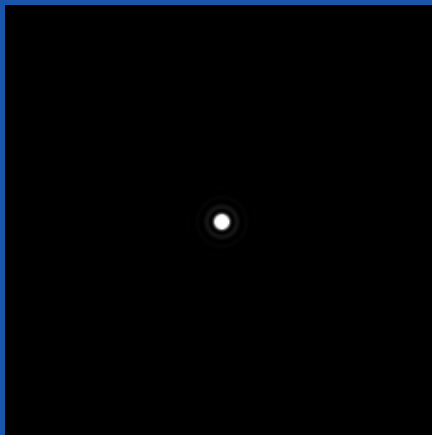
$$Z_0^0$$

Zernikepolynom

Vanlig benämning:

Medelvärde

PSF

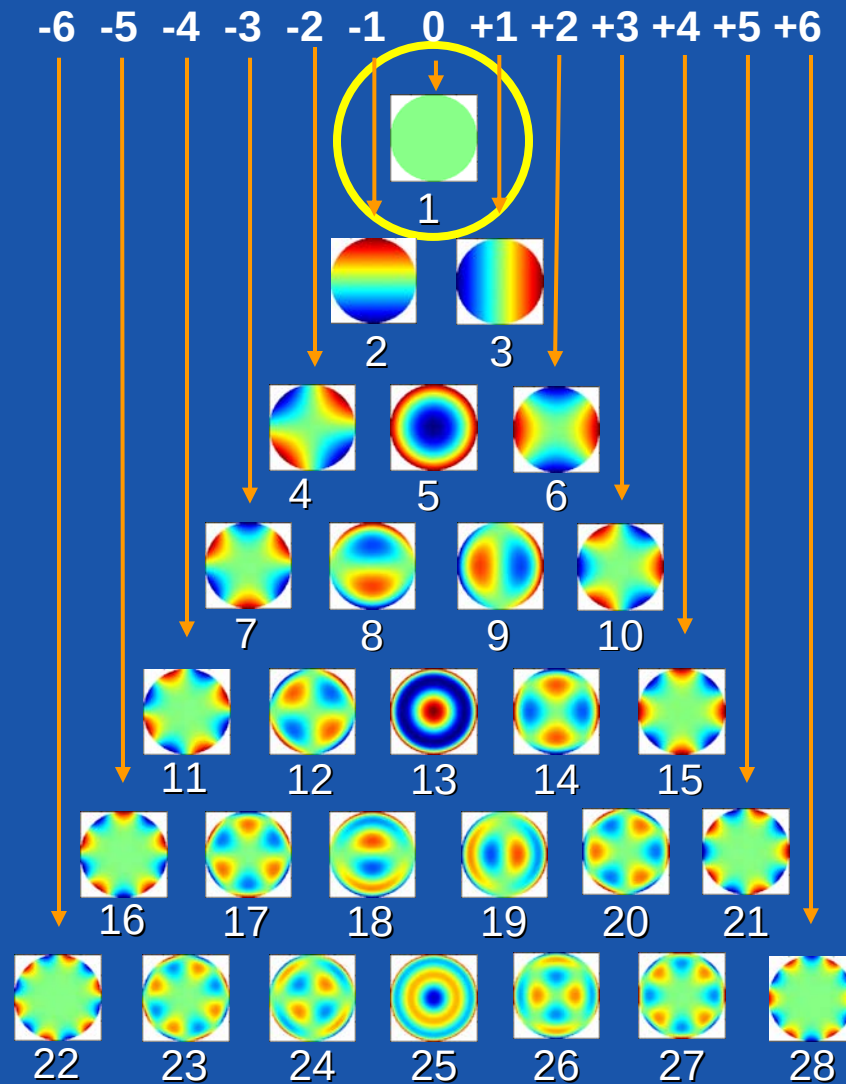


Bild



m = vinkelfrekvens

n = radiell
ordning



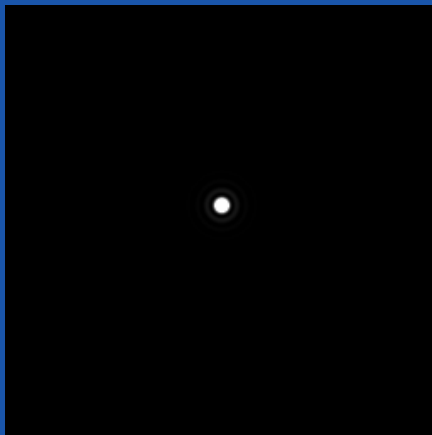
$$Z_1^{-1}$$

Zernikepolynom

Vanlig benämning:

Lutning

PSF

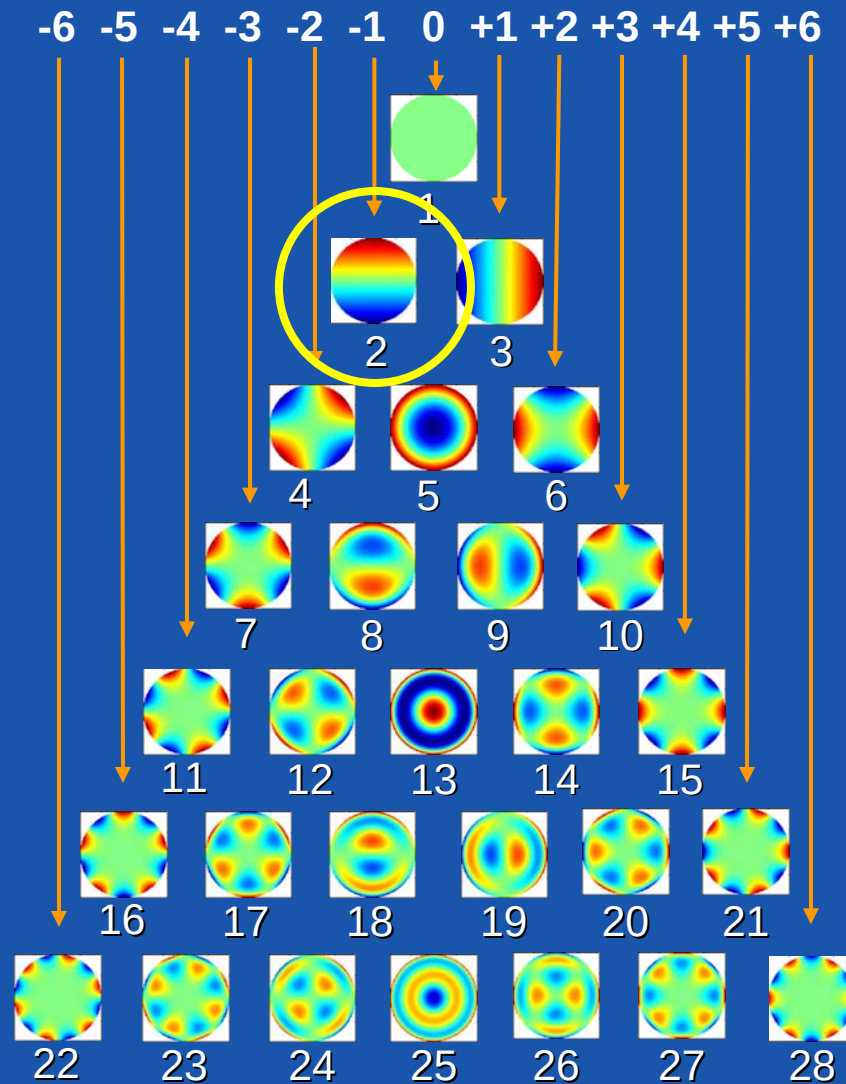


Bild



m = vinkelfrekvens

n = radiell
ordning



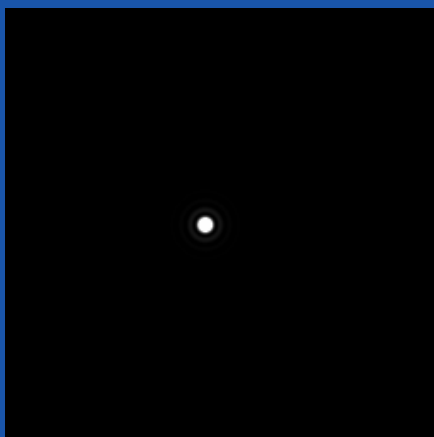
$$Z_1^1$$

Zernikepolynom

Vanlig benämning:

Lutning

PSF

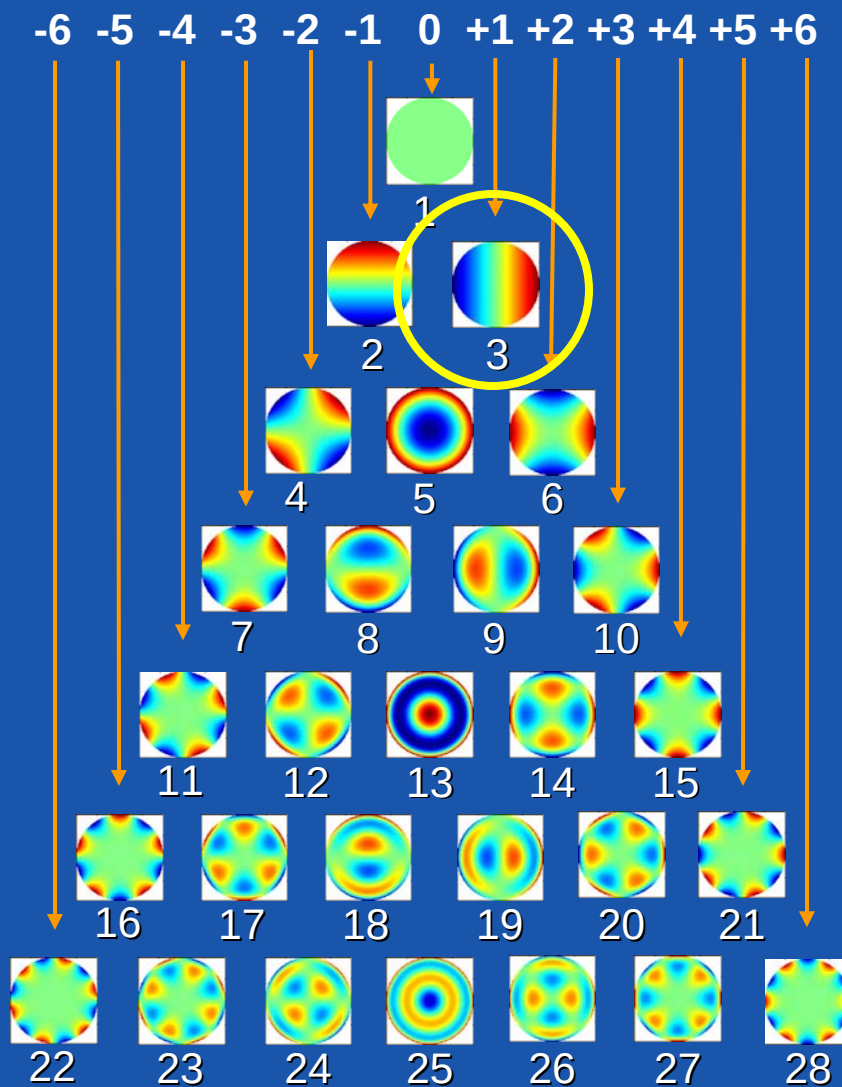


Bild



m = vinkelfrekvens

n = radiell
ordning



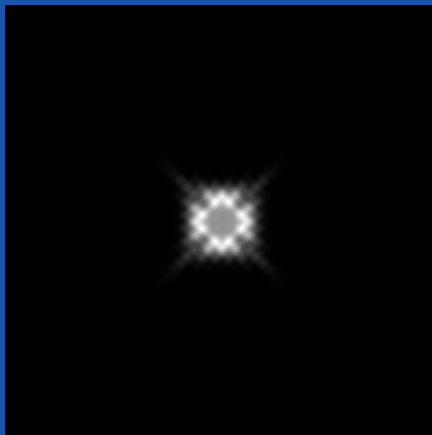
$$Z_2^{-2}$$

Zernikepolynom

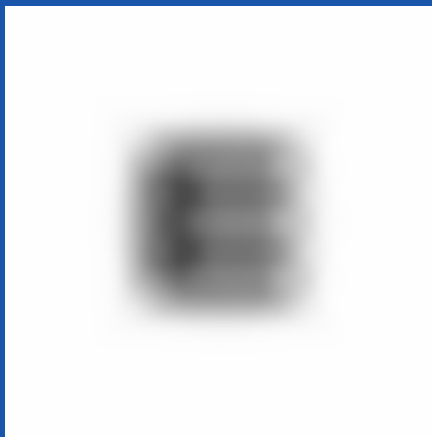
Vanlig benämning:

Astigmatism

PSF

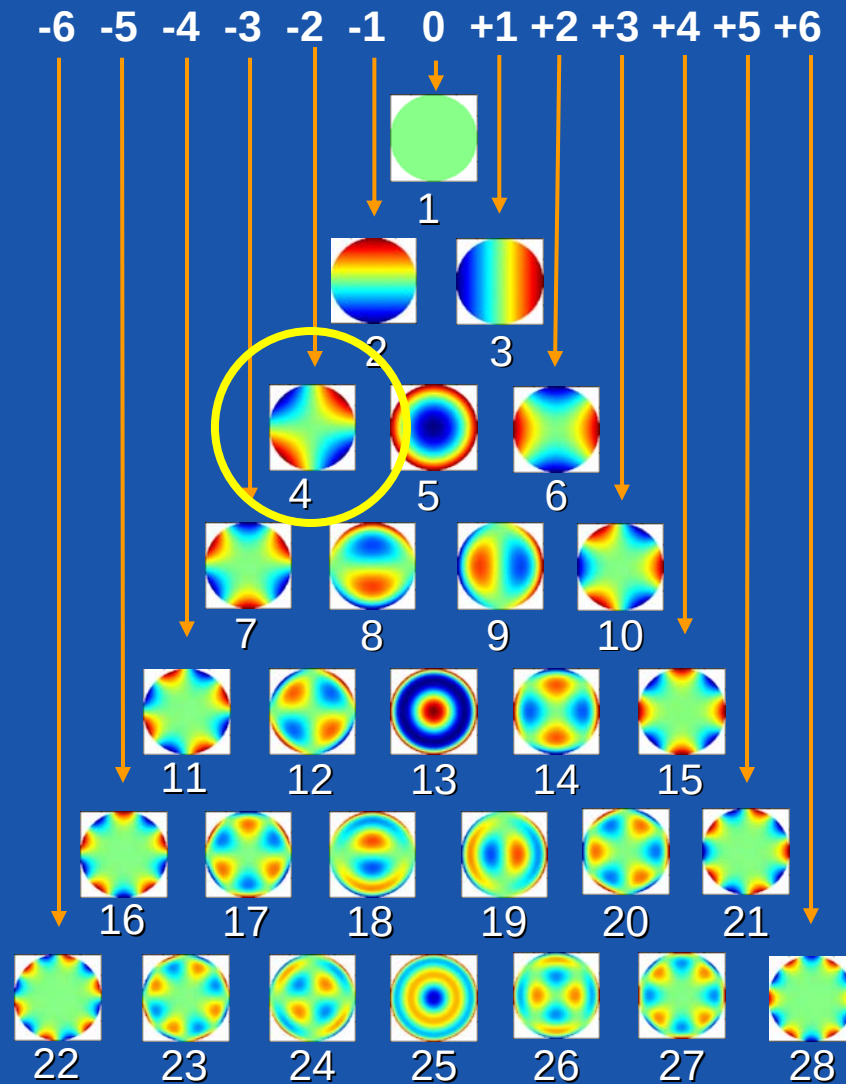


Bild



m = vinkelfrekvens

n = radiell
ordning



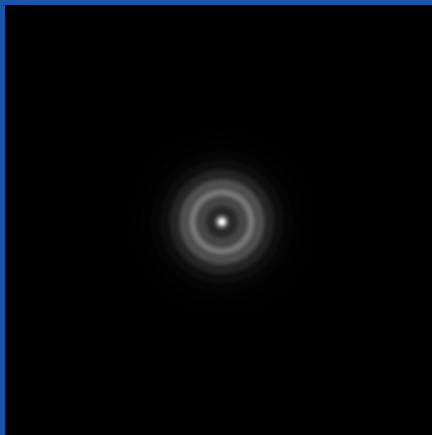
$$Z_2^0$$

Zernikepolynom

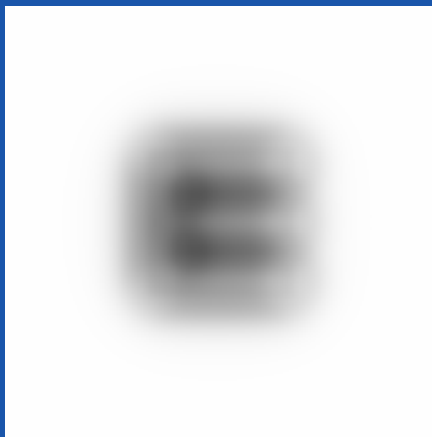
Vanlig benämning:

Defokus

PSF

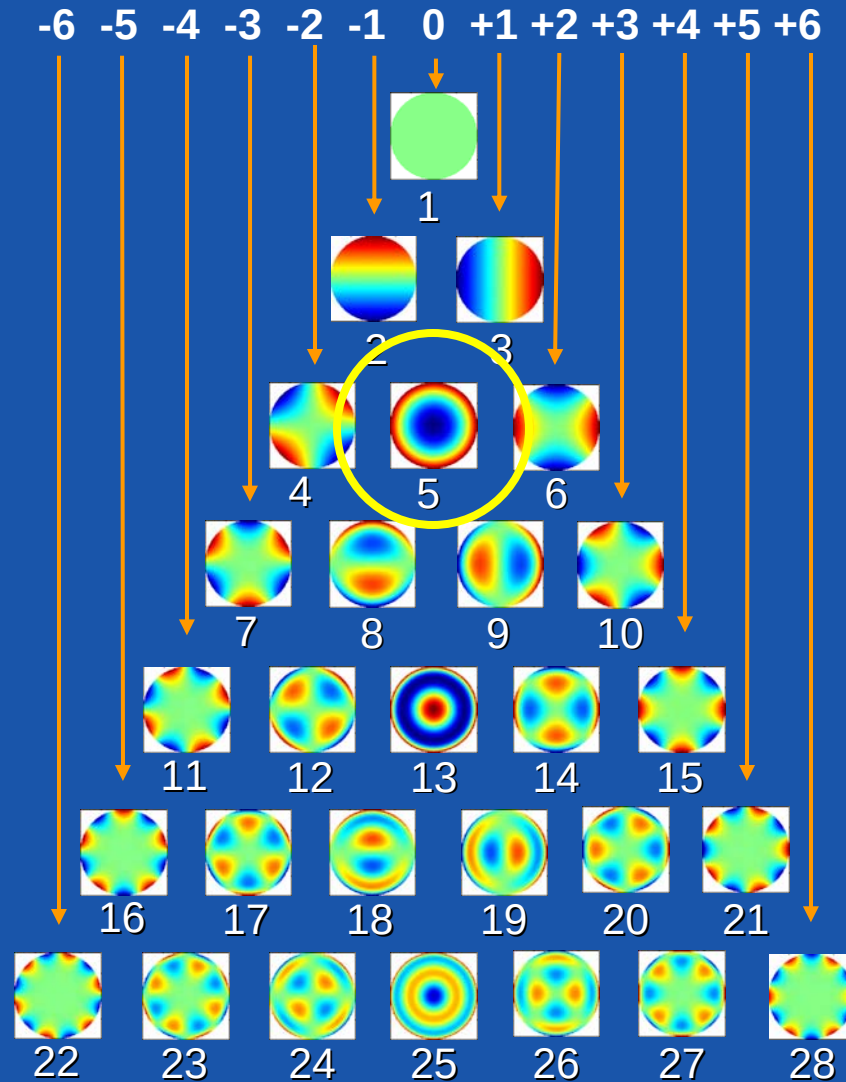


Bild



m = vinkelfrekvens

n = radiell
ordning



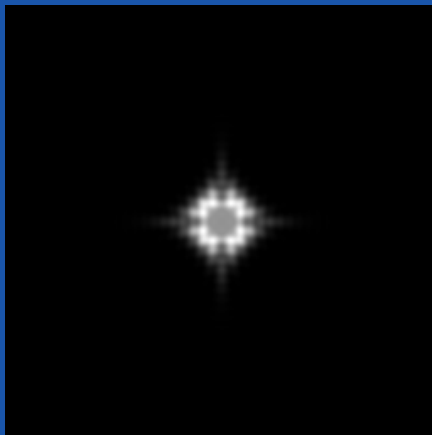
$$Z_2^2$$

Zernikepolynom

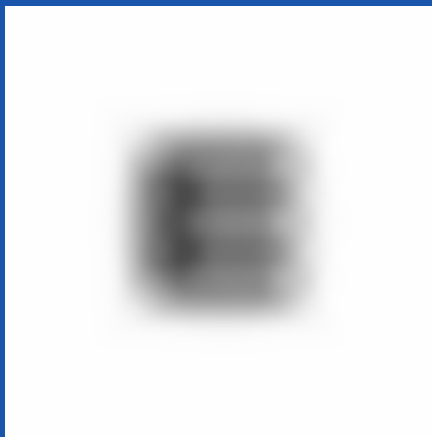
Vanlig benämning:

Astigmatism

PSF

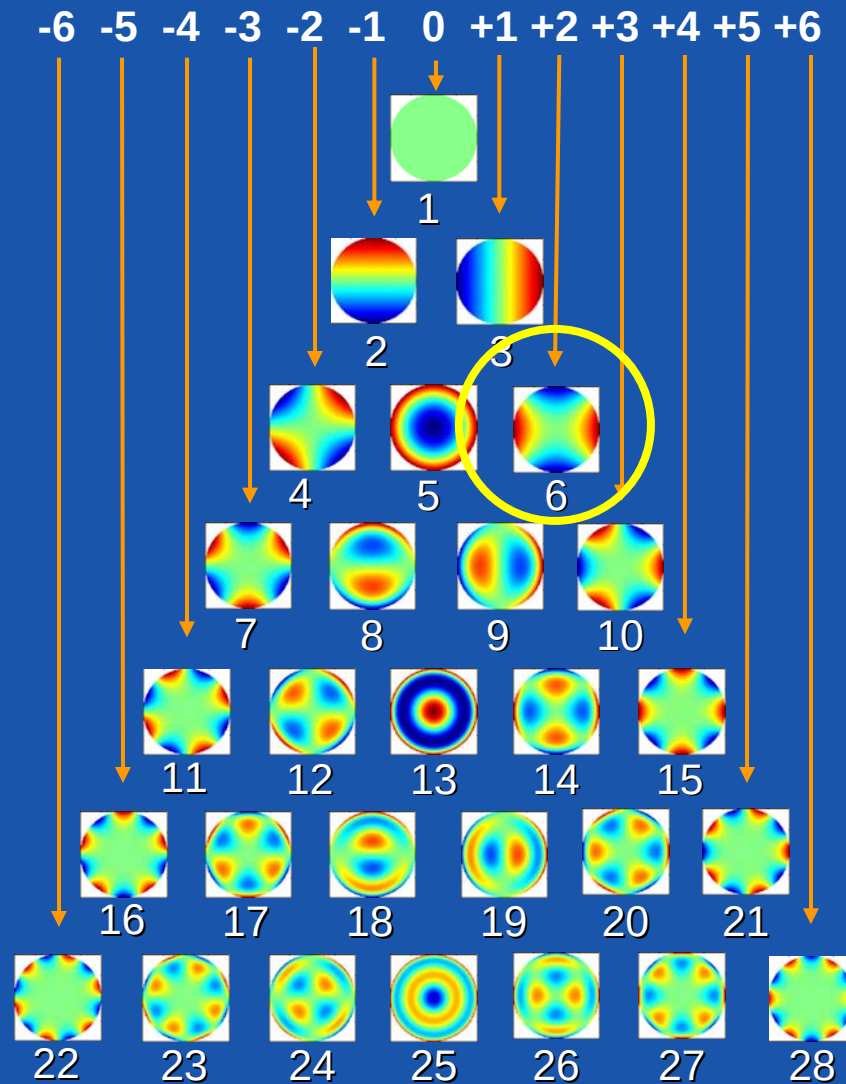


Bild



m = vinkelfrekvens

n = radiell
ordning



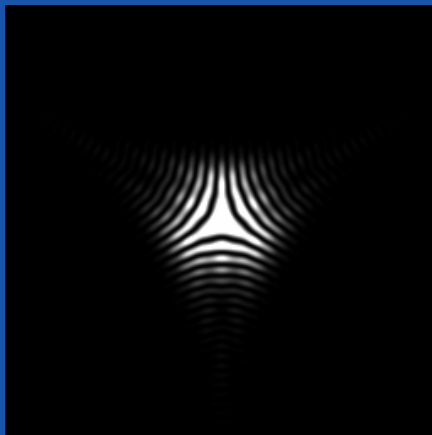
$$Z_3^{-3}$$

Zernikepolynom

Vanlig benämning:

Trefoil

PSF

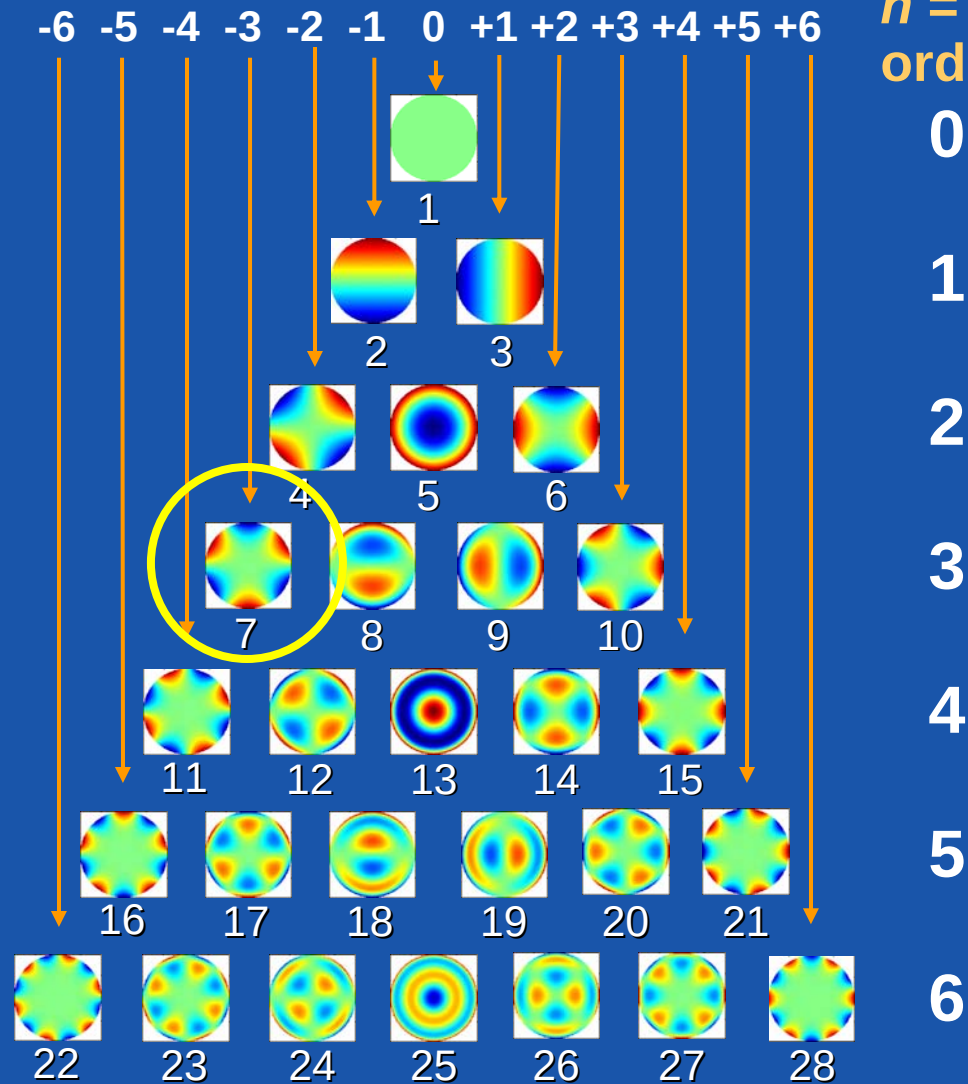


Bild



m = vinkelfrekvens

n = radiell
ordning



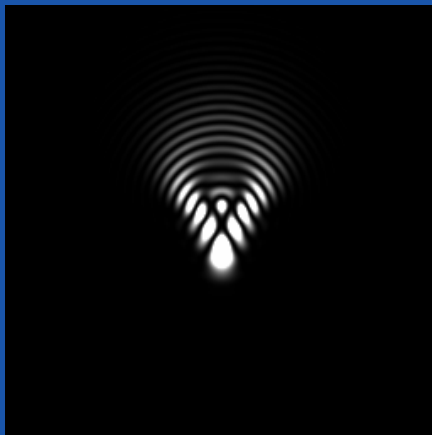
$$Z_3^{-1}$$

Zernikepolynom

Vanlig benämning:

Koma

PSF

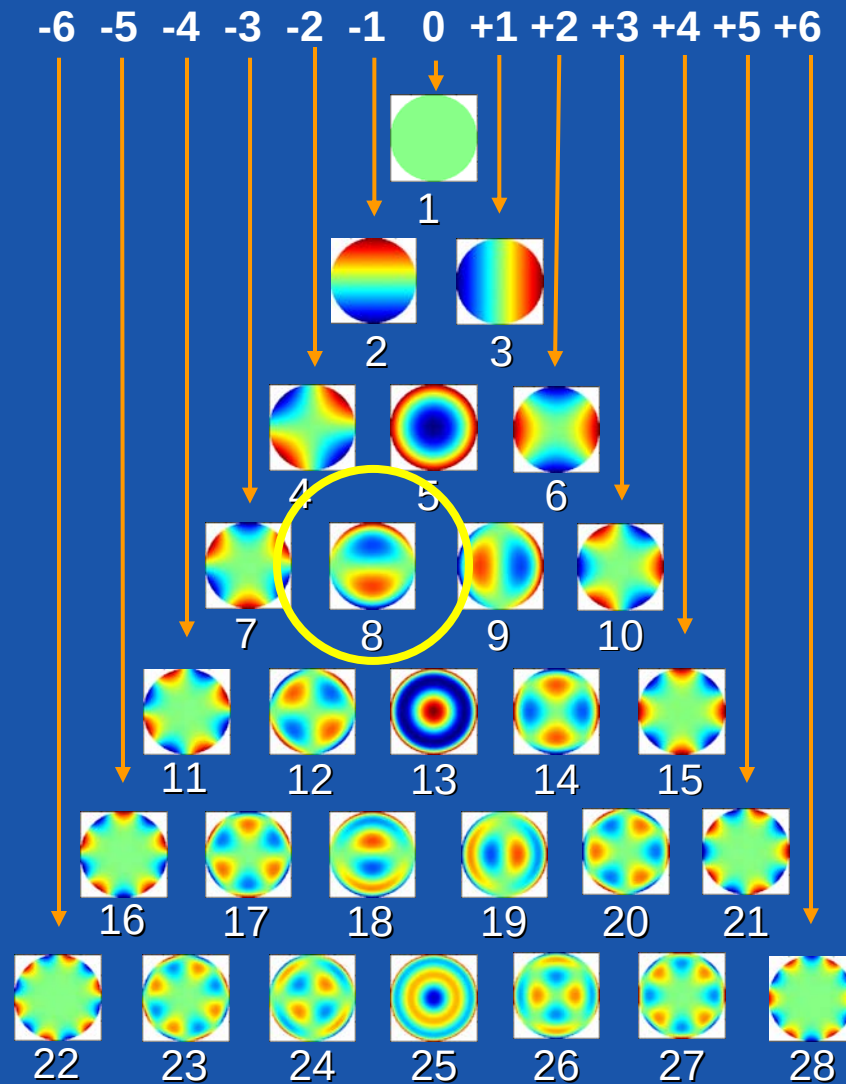


Bild



m = vinkelfrekvens

n = radiell
ordning



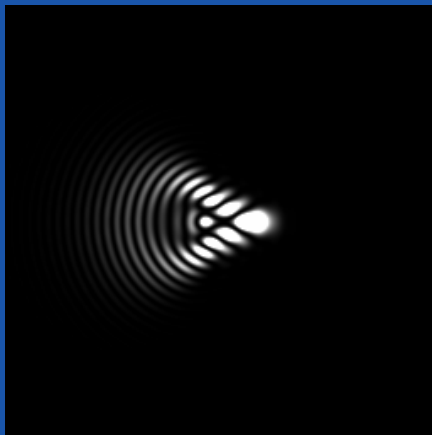
$$Z_3^1$$

Zernikepolynom

Vanlig benämning:

Koma

PSF

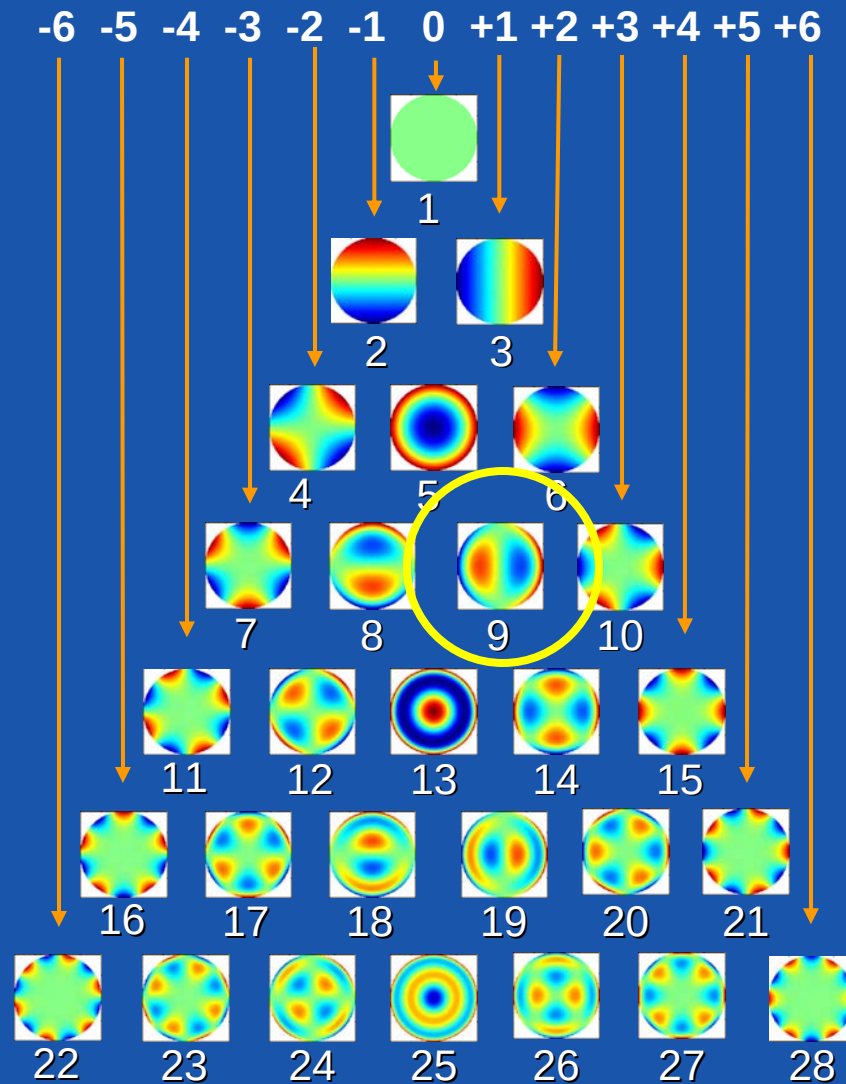


Bild



m = vinkelfrekvens

n = radiell
ordning



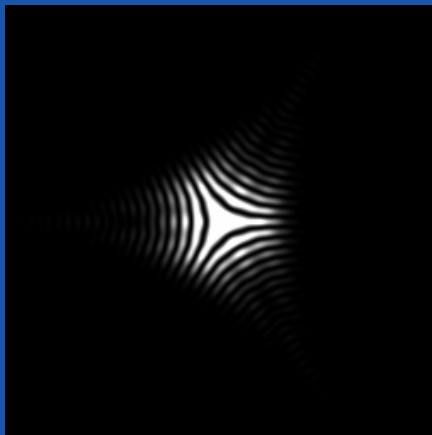
$$Z_3^3$$

Zernikepolynom

Vanlig benämning:

Trefoil

PSF

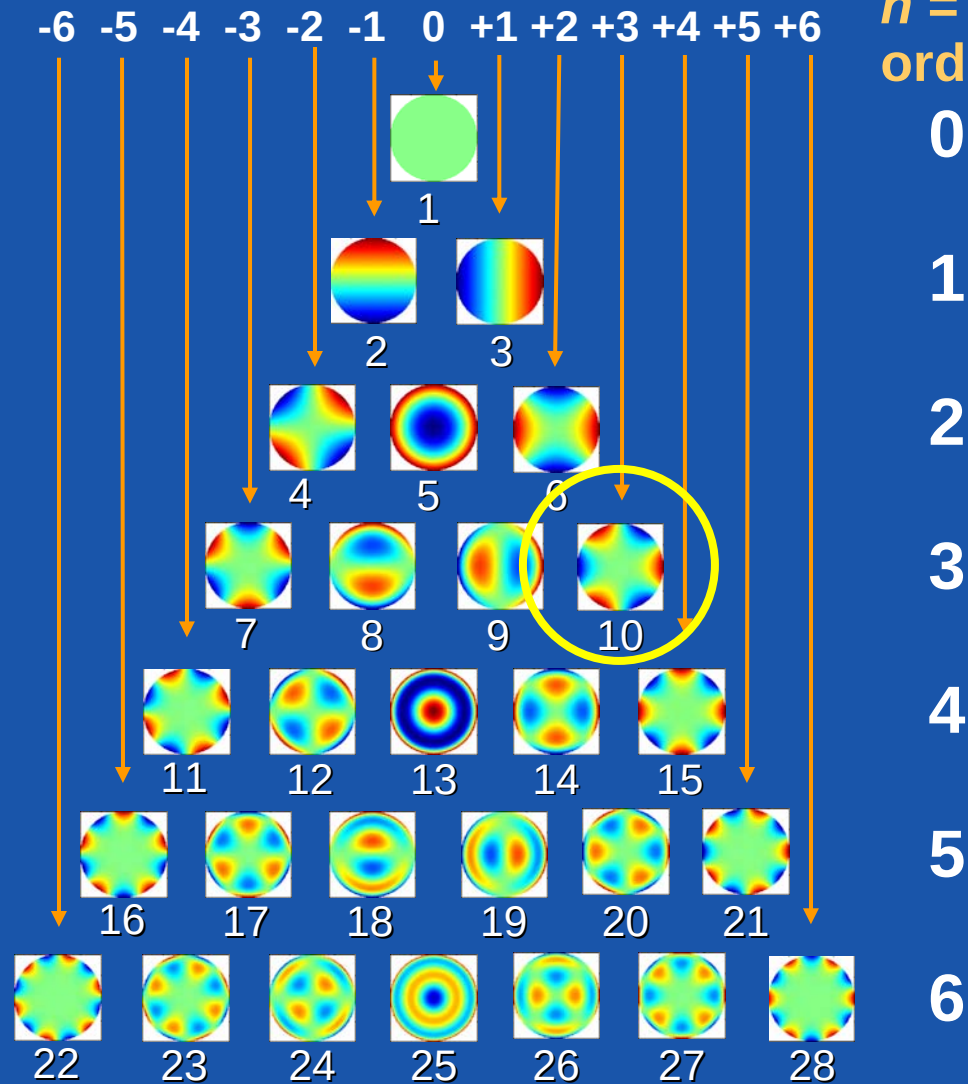


Bild



m = vinkelfrekvens

n = radiell
ordning



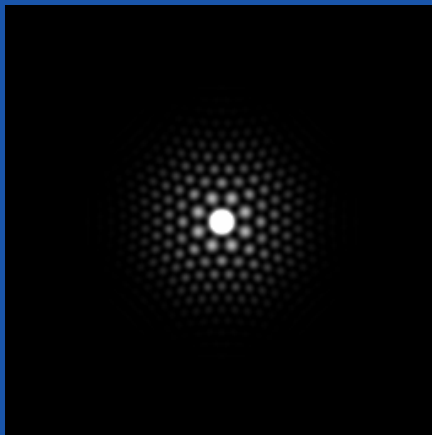
$$Z_4^{-4}$$

Zernikepolynom

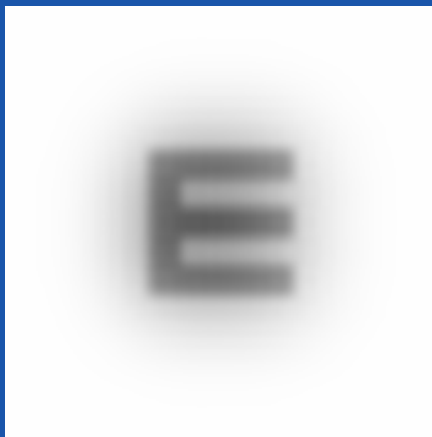
Vanlig benämning:

Quadrafoil

PSF

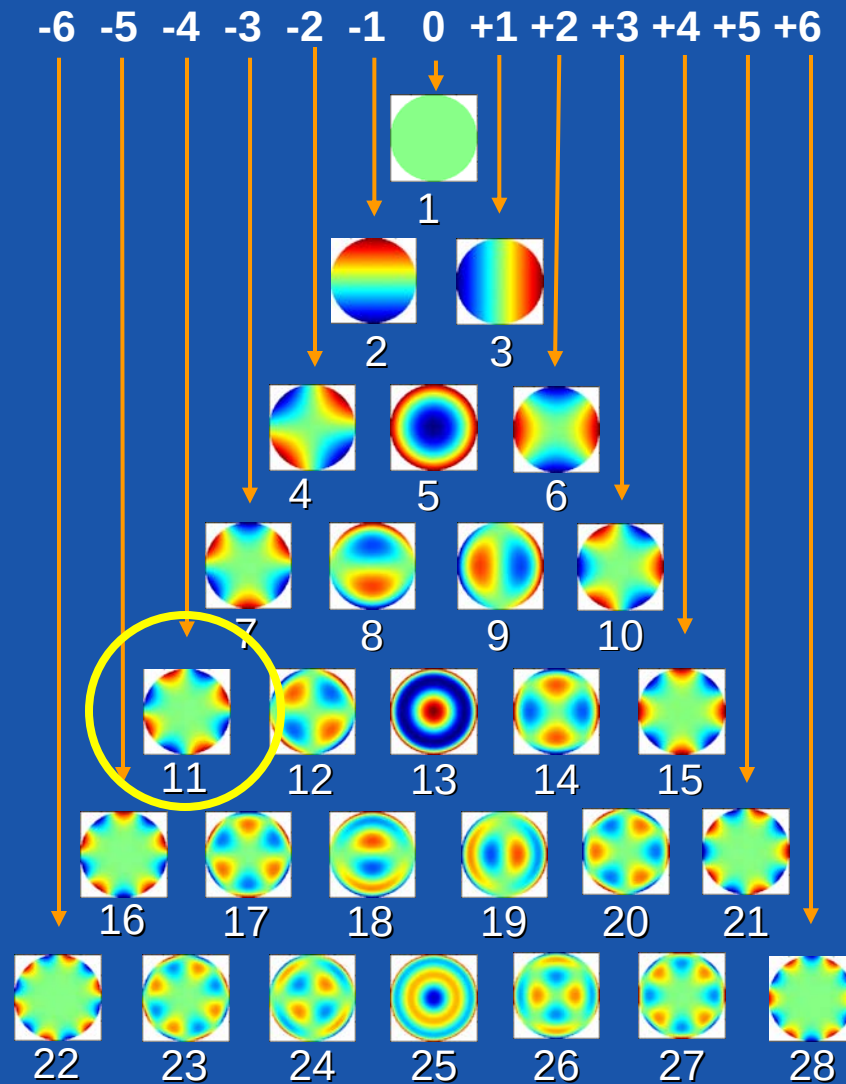


Bild



m = vinkelfrekvens

n = radiell
ordning

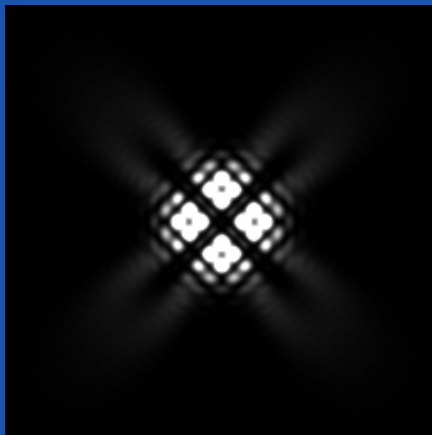


$$Z_4^{-2}$$

Zernikepolynom

Vanlig benämning:
Sekundär astigmatism

PSF

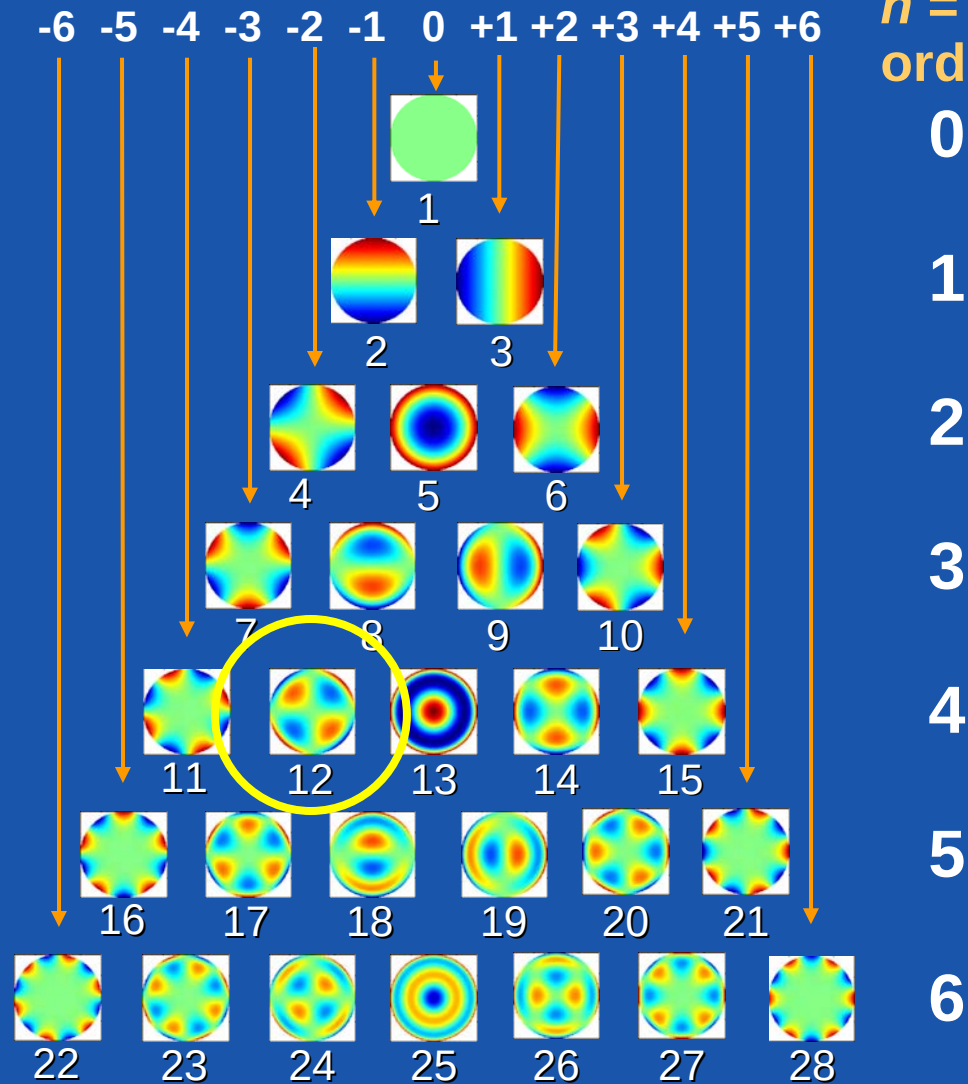


Bild



m = vinkelfrekvens

**n = radiell
ordning**



$$Z_4^0$$

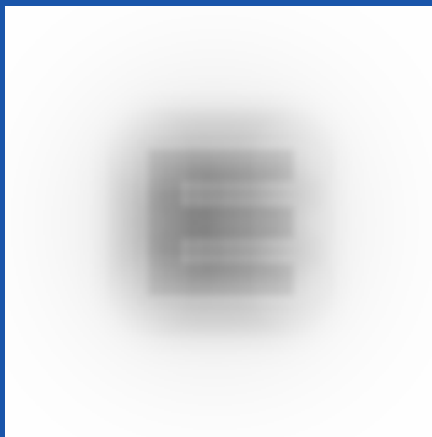
Zernikepolynom

Vanlig benämning:
Sfärisk aberration

PSF

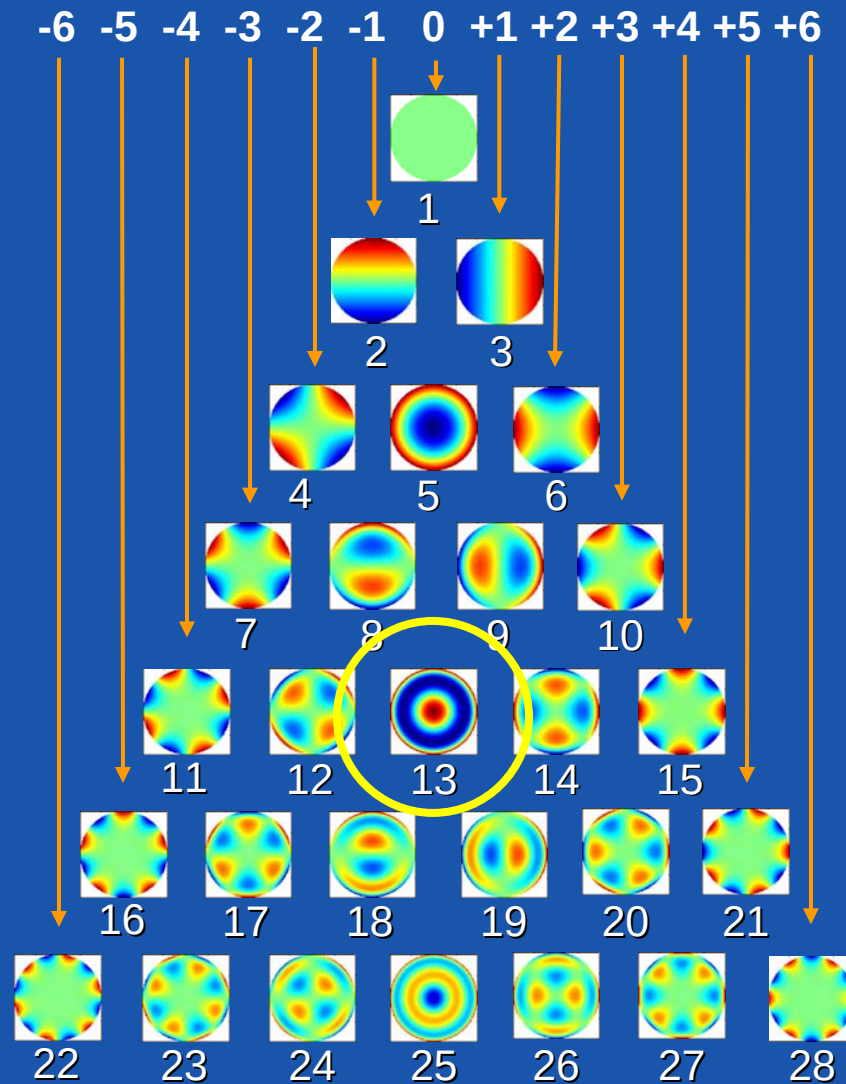


Bild



m = vinkelfrekvens

n = radiell
ordning

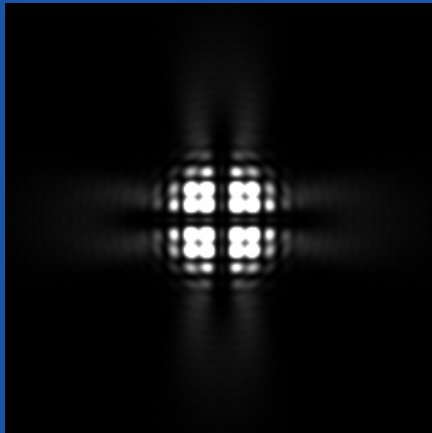


$$Z_4^2$$

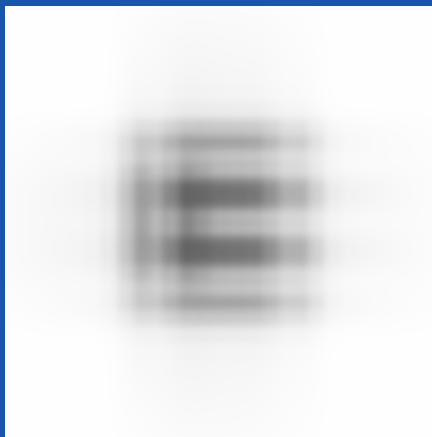
Zernikepolynom

Vanlig benämning:
Sekundär astigmatism

PSF

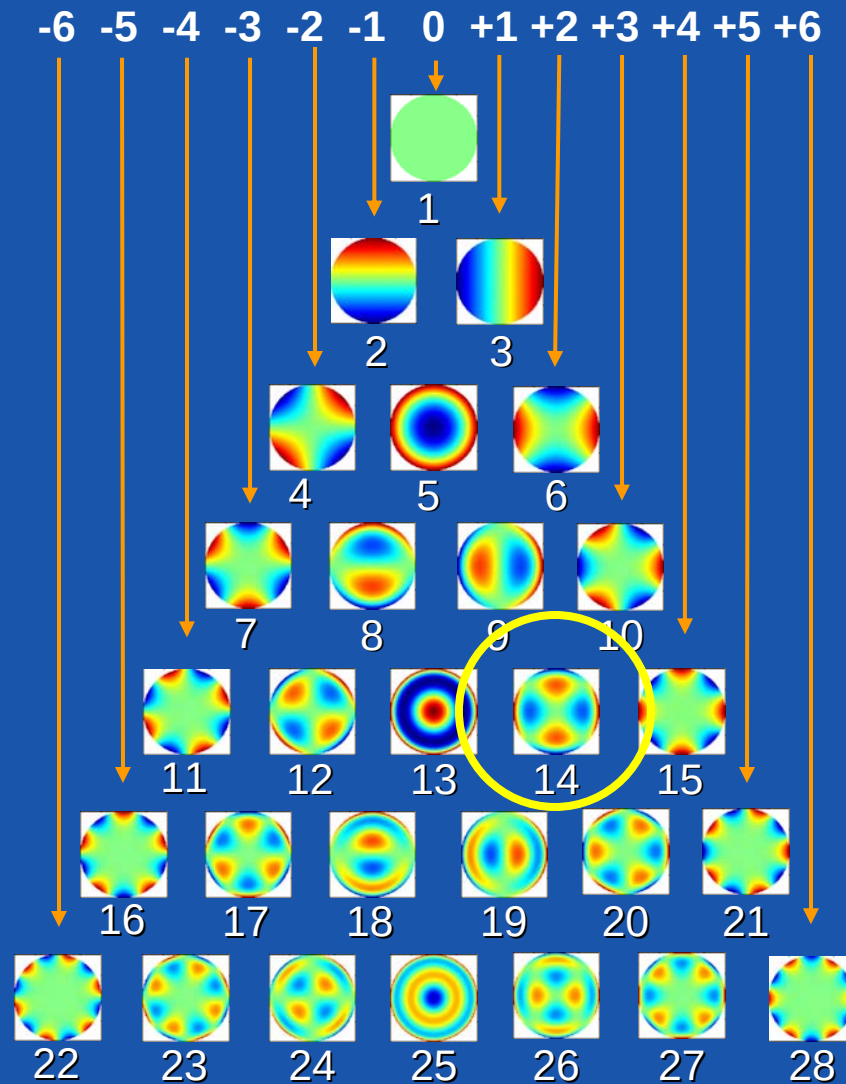


Bild



m = vinkelfrekvens

**n = radiell
ordning**



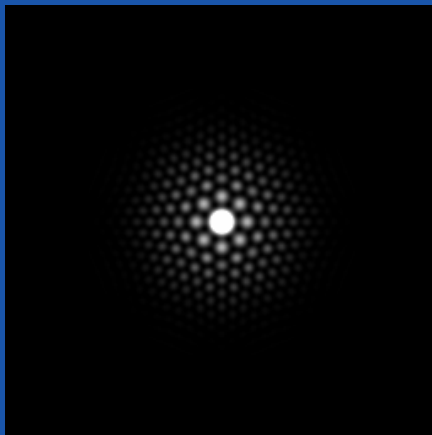
$$Z_4^4$$

Zernikepolynom

Vanlig benämning:

Quadrafoil

PSF

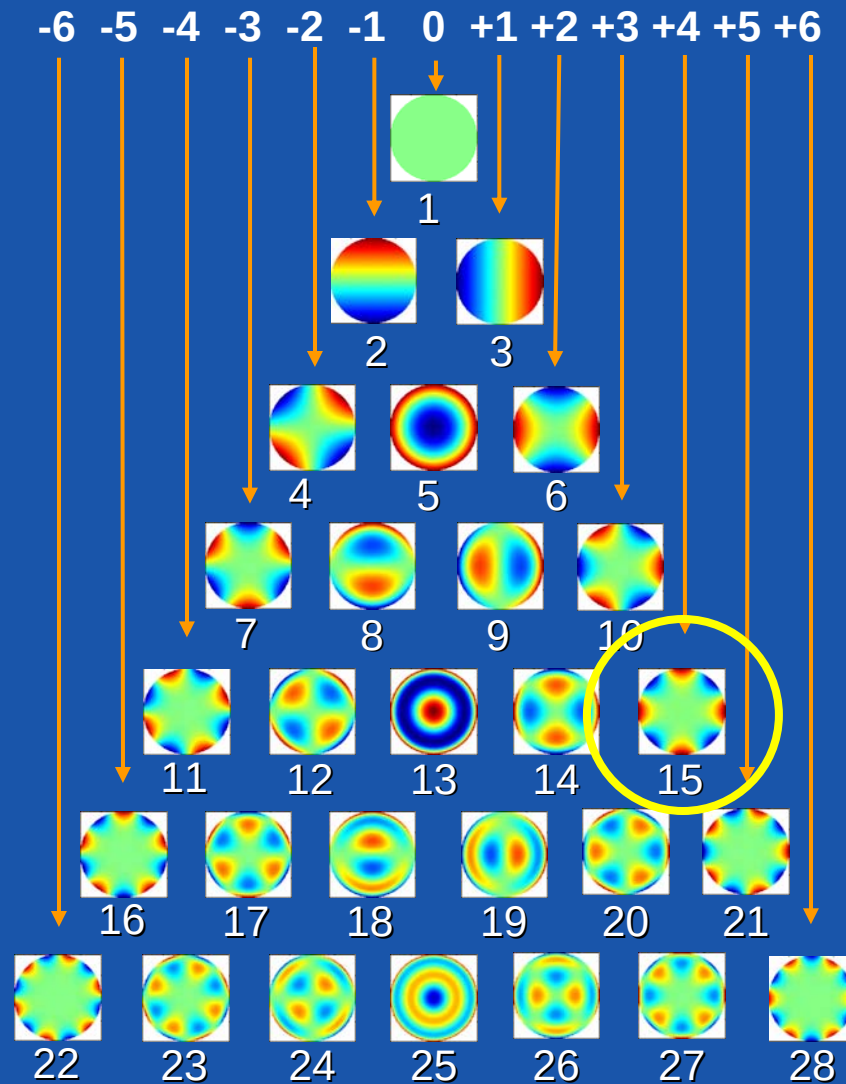


Bild

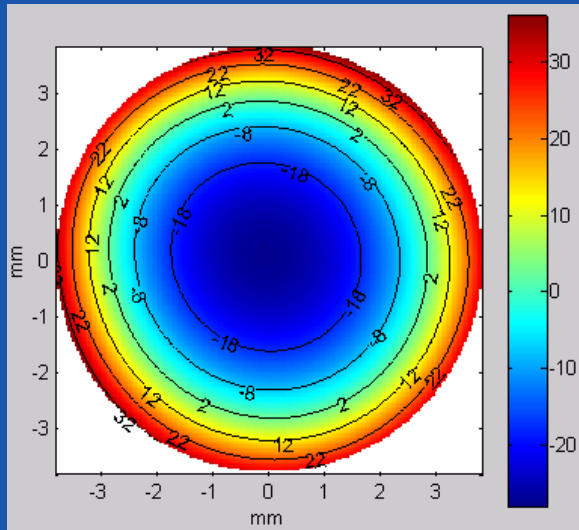


m = vinkelfrekvens

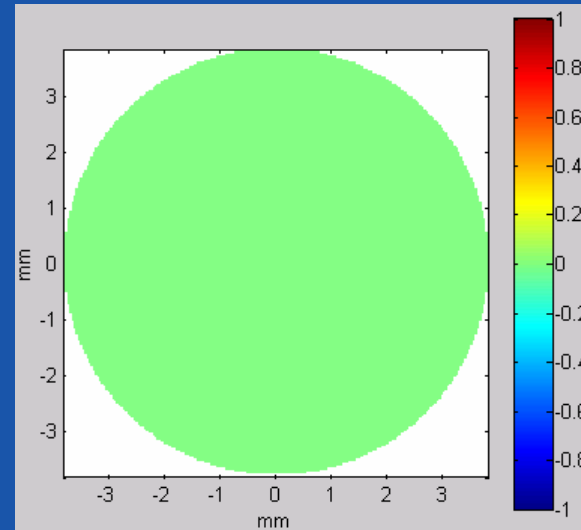
n = radiell
ordning



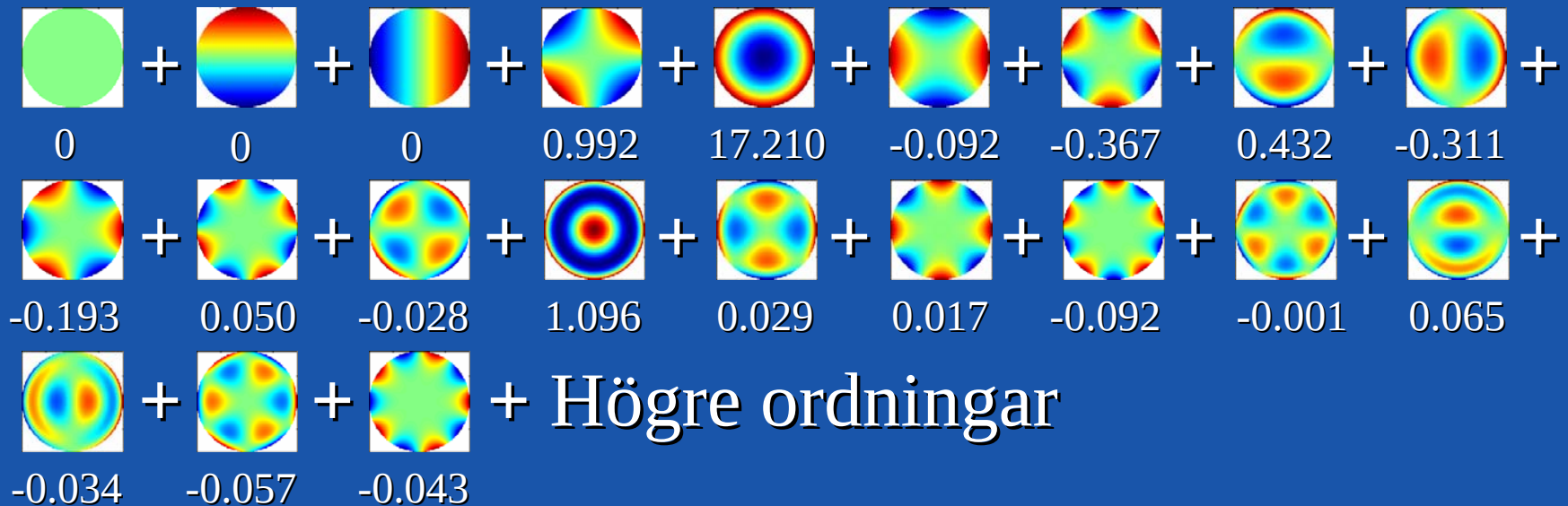
Zernikekoefficienter



=

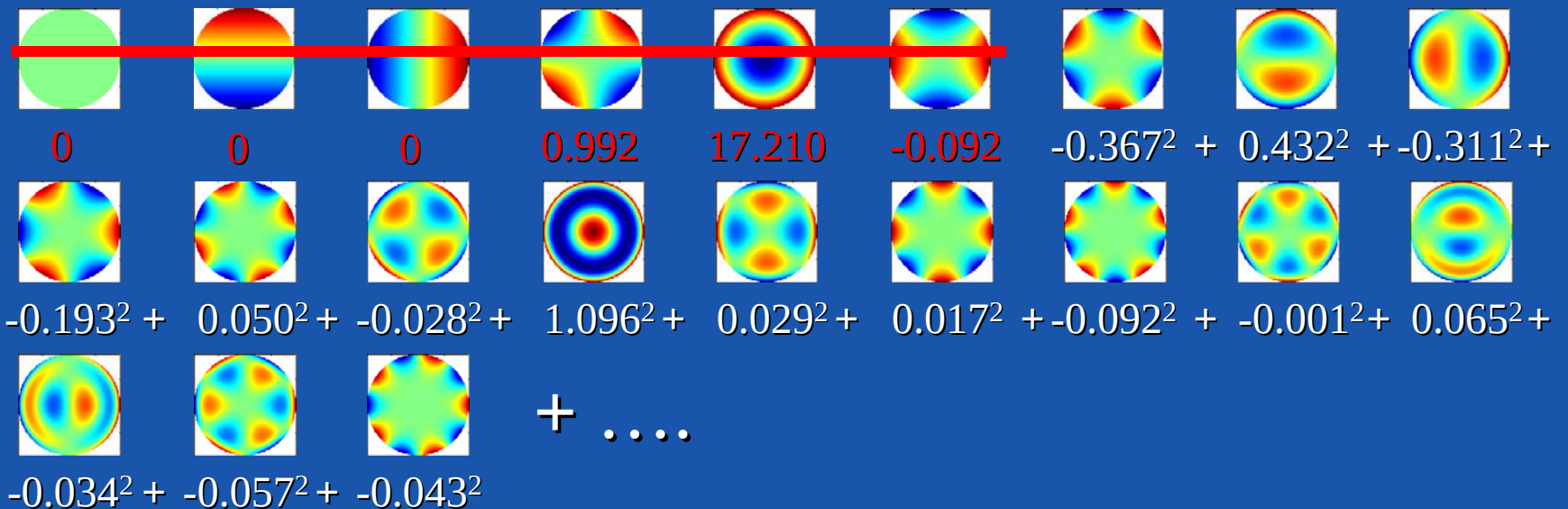


+



Hur mycket aberrationer brukar man ha?

Högre ordnings (HO) RMS =



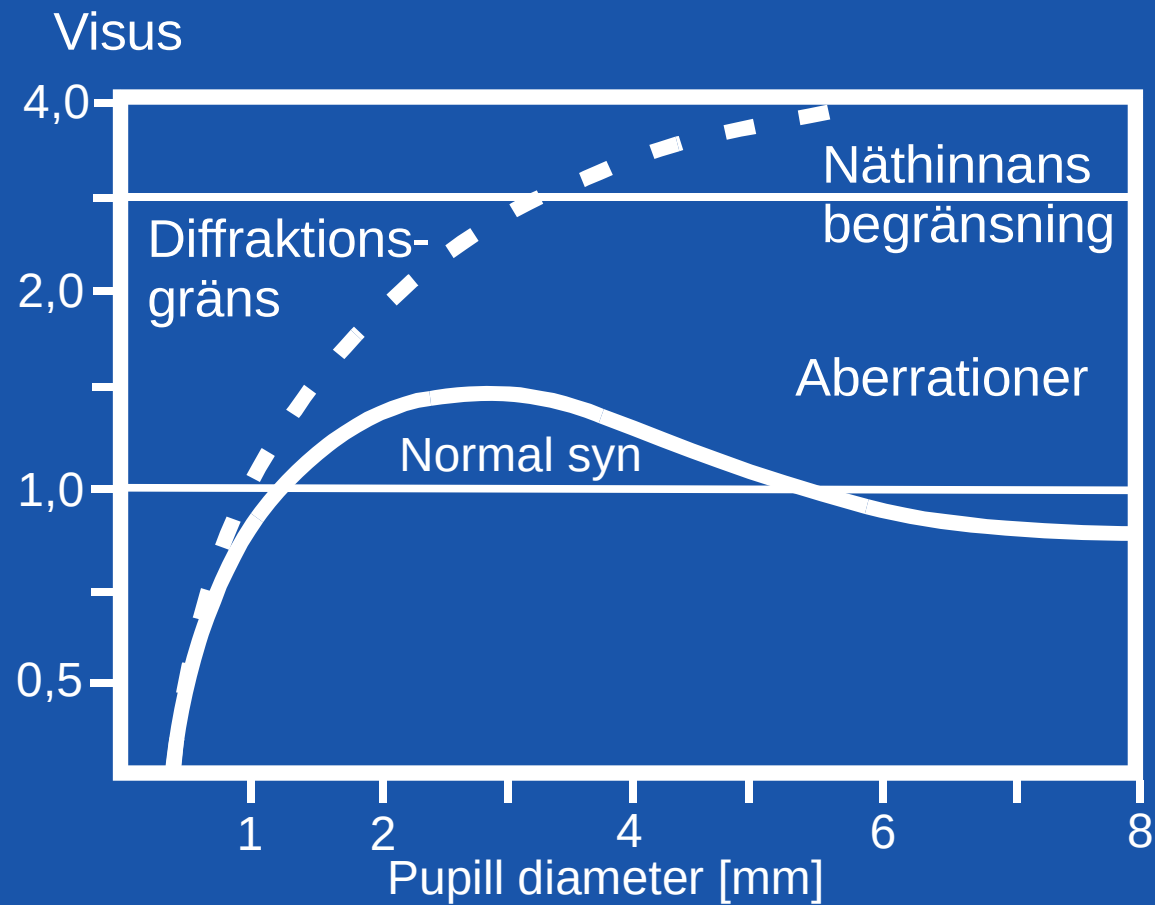
= 1.3 μm (0.5 μm vid 6 mm pupill)

Normalt HO RMS < 0.5 μm vid 6 mm pupill

Vågfrontsrecept

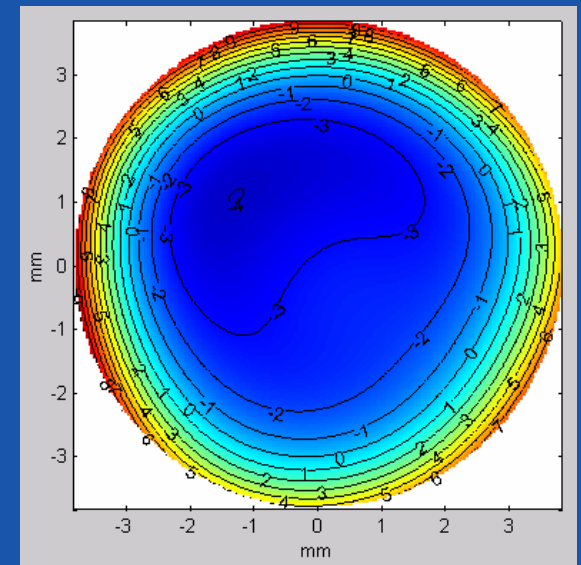
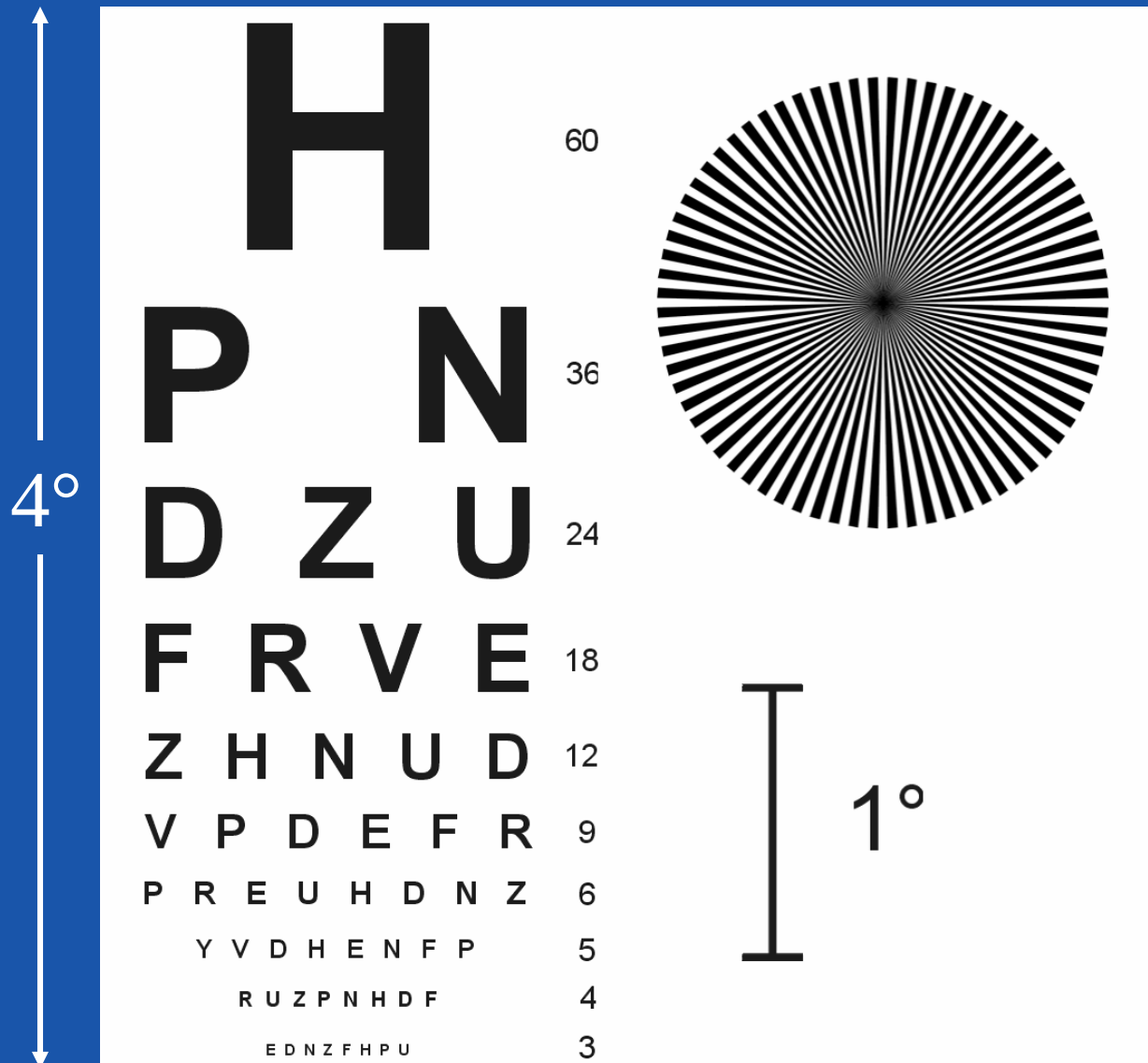
Mode	Coeff [μm]	Benämning
Z_2^{-2}	0.4825	Astigm. 45°/135°
Z_2^0	4.4171	Defokus
Z_2^2	-0.2316	Astigm. 0°/90°
Z_3^{-3}	-0.0073	Vertikal trefoil
Z_3^{-1}	-0.1273	Vertikal koma
Z_3^1	-0.0709	Horisontell koma
Z_3^3	0.0660	Sned trefoil
Z_4^{-4}	-0.0120	Quadrafoil
Z_4^{-2}	0.0140	Sekundär astigm
Z_4^0	0.1937	Sfärisk aberration
Z_4^2	0.0743	Sekundär astigm
Z_4^4	0.0236	Quadrafoil
Analysdiameter	5.798 mm	
Total RMS	4.457 μm	
Högre ordn. RMS	0.264 μm	
3:e ordn. RMS	0.160 μm	
4:e ordn. RMS	0.210 μm	

Hur påverkas synen?



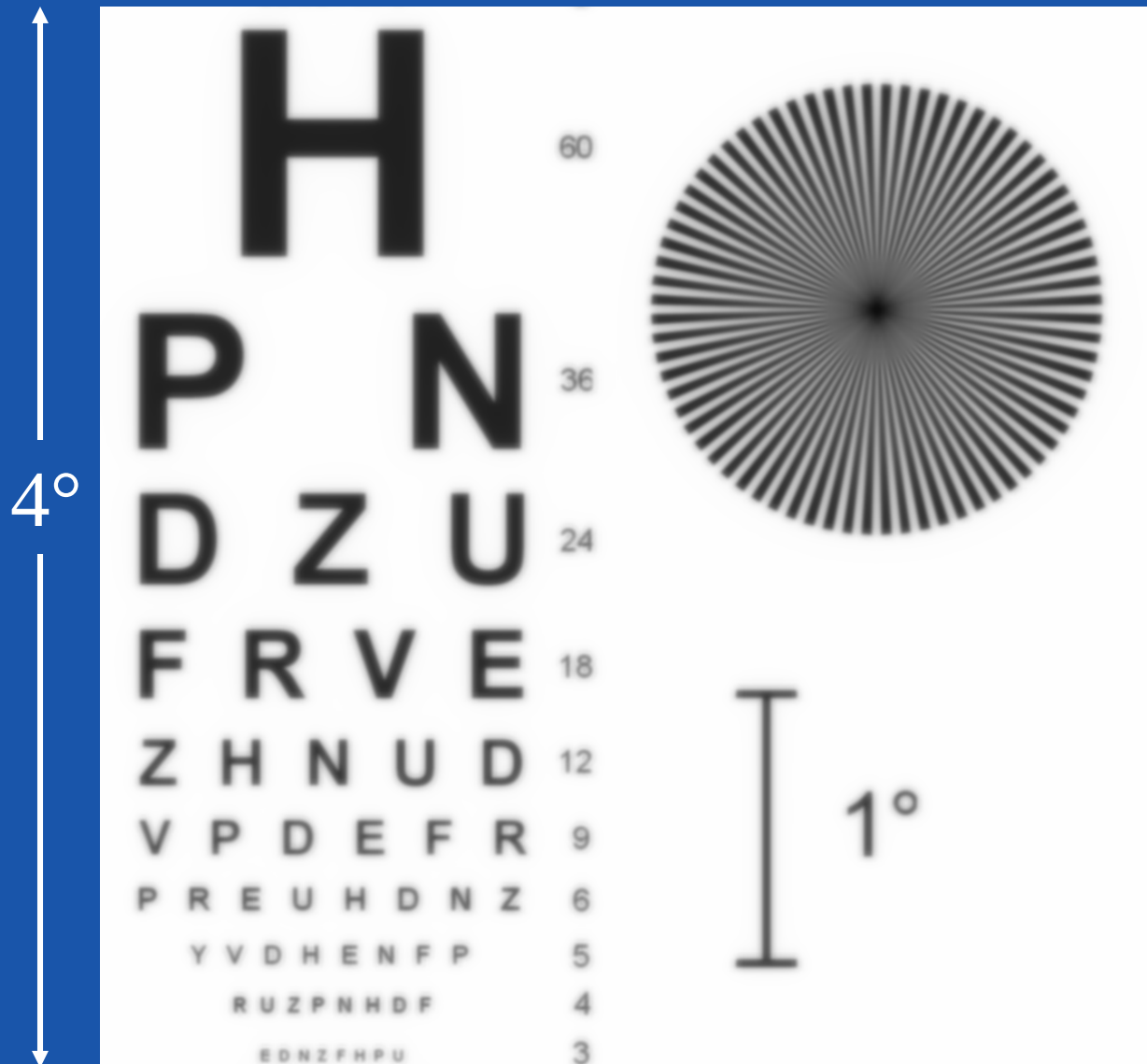
Hur påverkas synen?

Hög kontrast

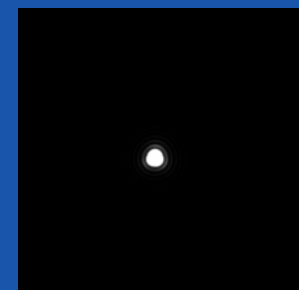
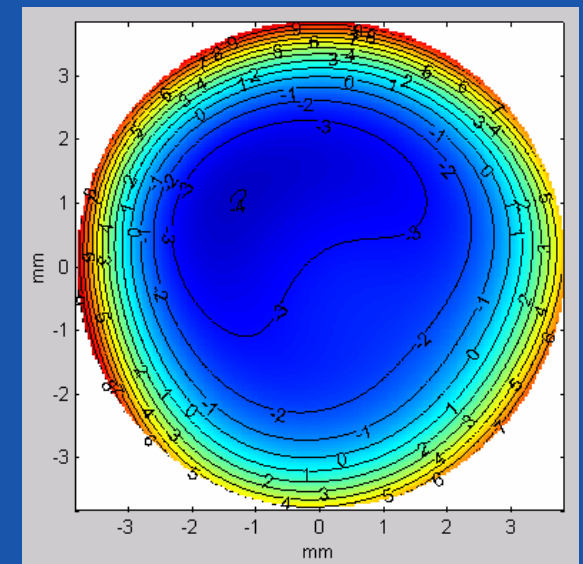


Hur påverkas synen?

Hög kontrast



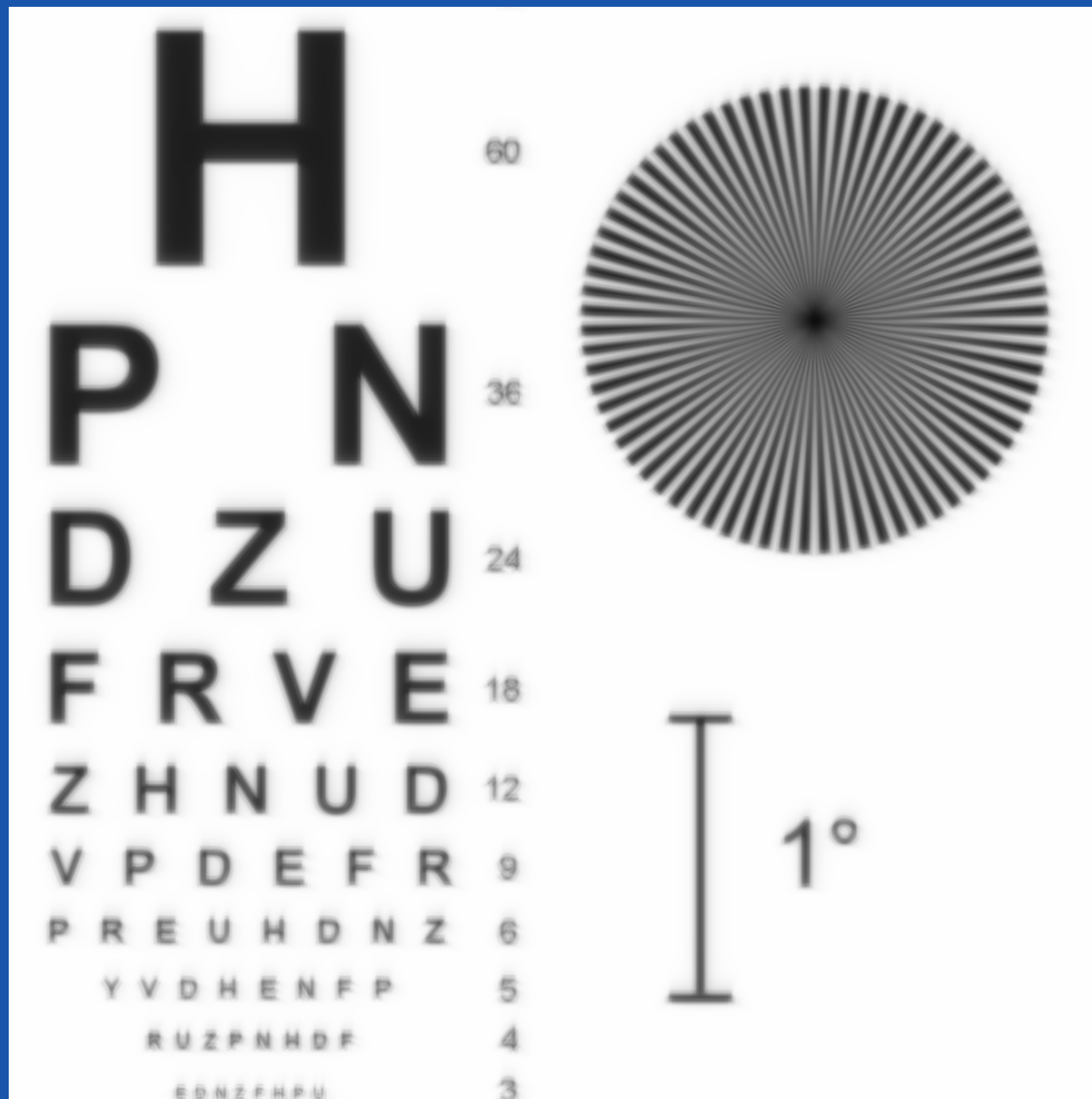
2 mm pupil



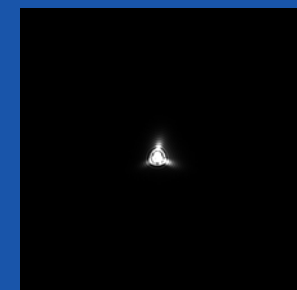
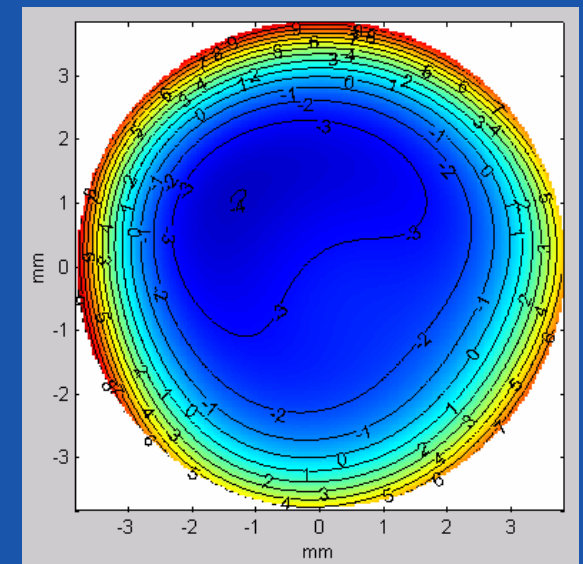
Hur påverkas synen?

Hög kontrast

4°



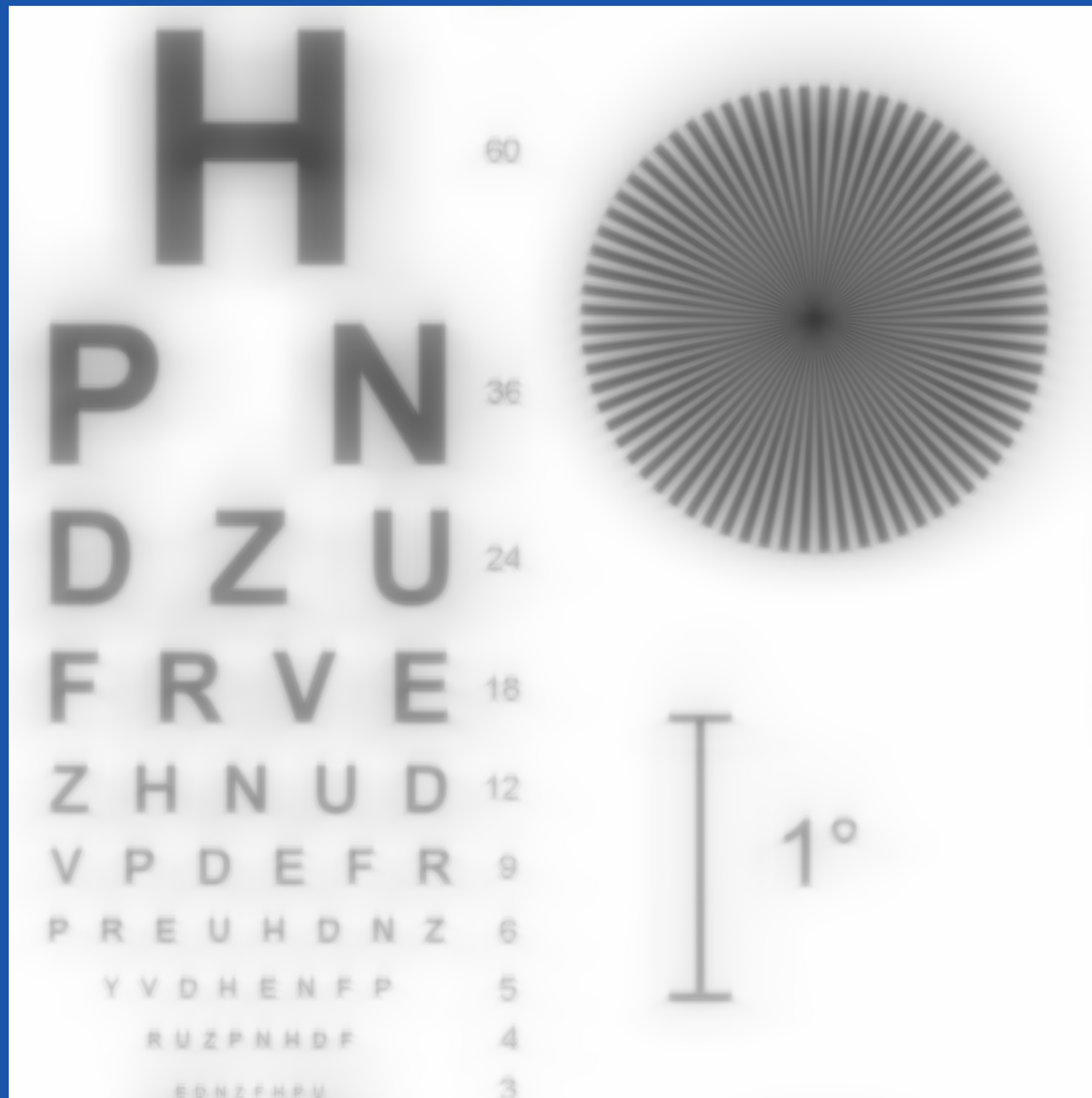
4 mm pupil



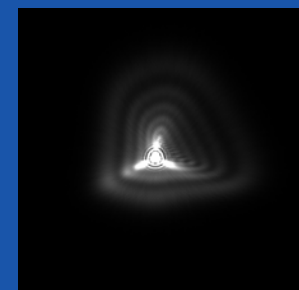
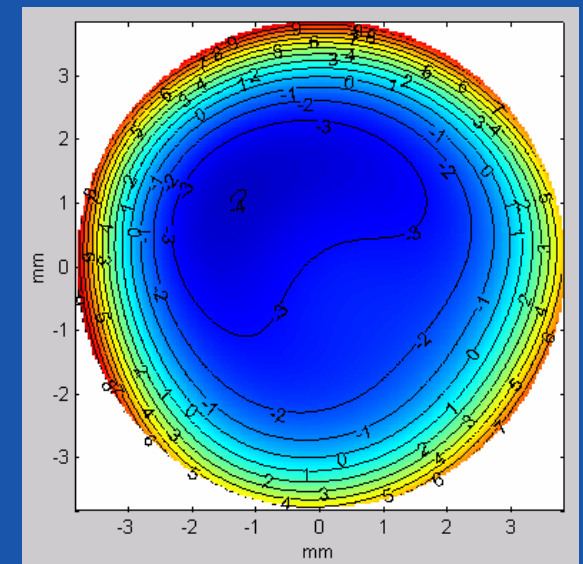
Hur påverkas synen?

Hög kontrast

4°



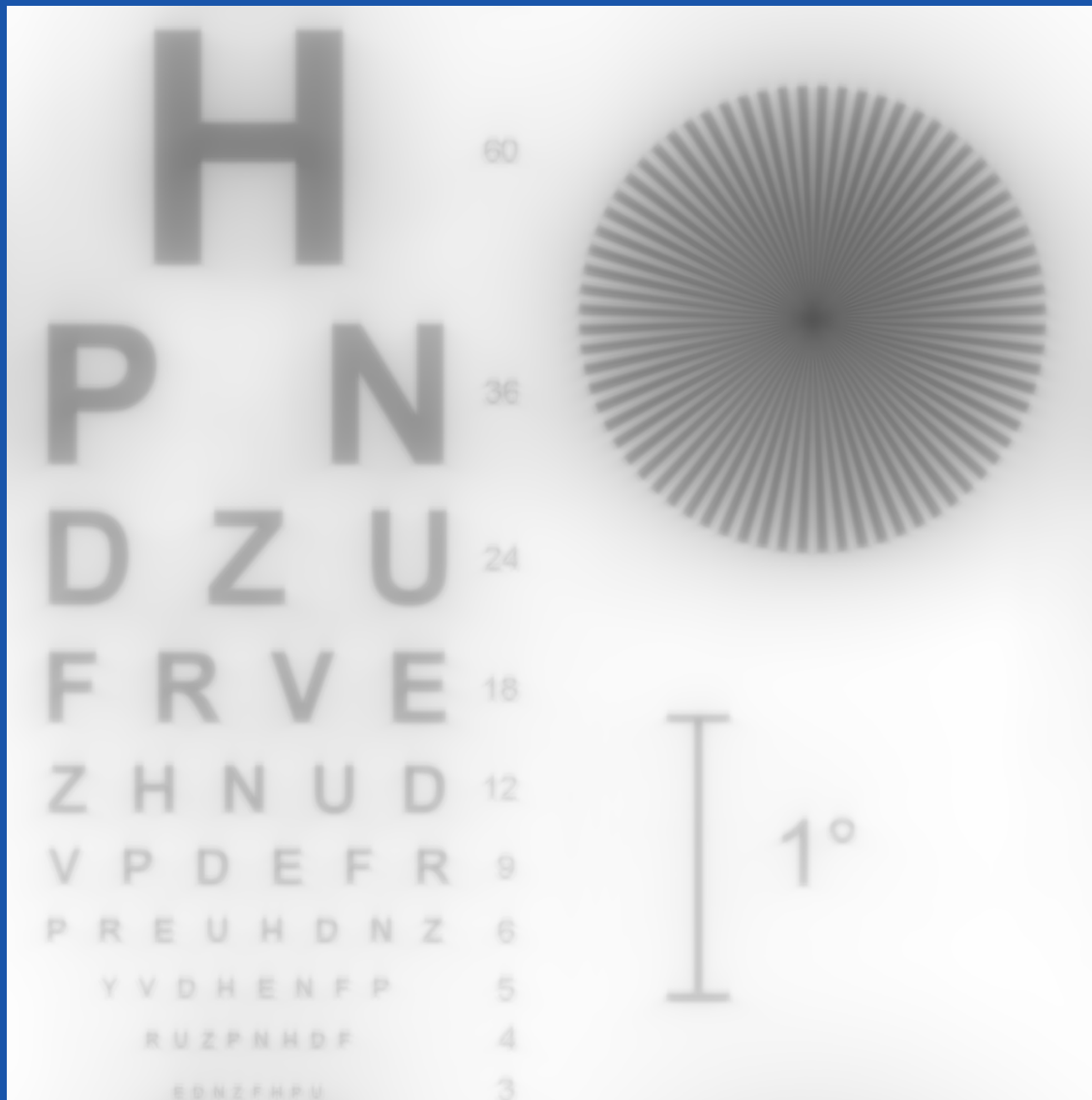
6 mm pupil



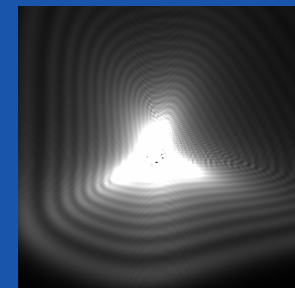
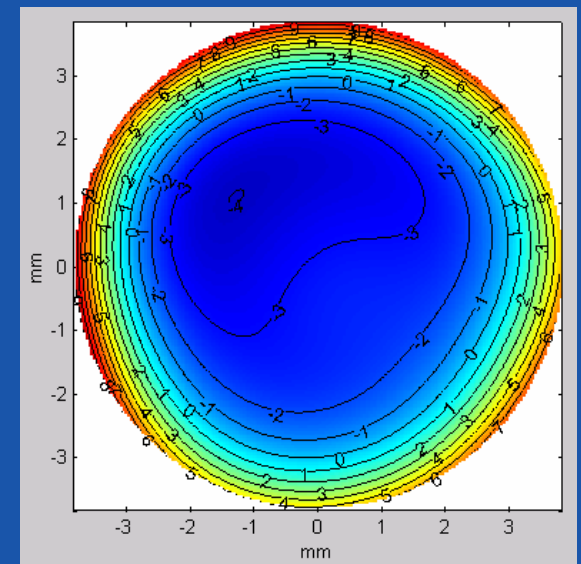
Hur påverkas synen?

Hög kontrast

4°



7,7 mm pupil



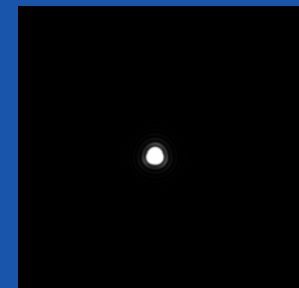
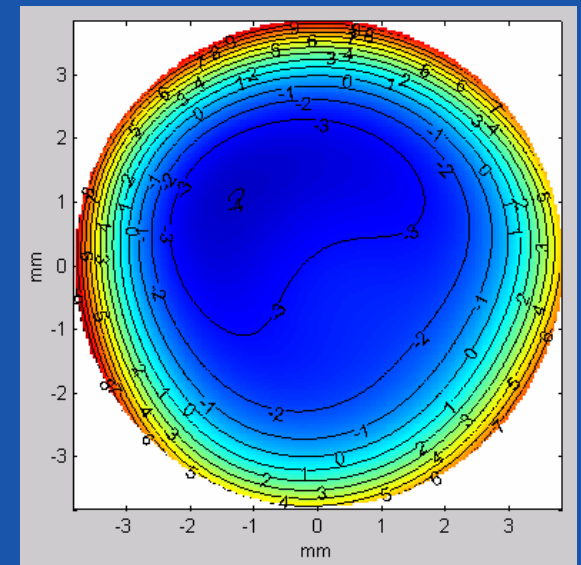
Hur påverkas synen?

Mörkerkörning

4°



2 mm pupil



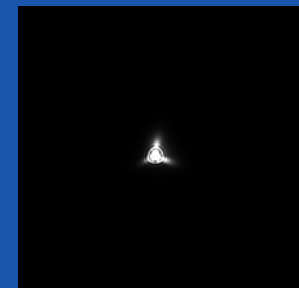
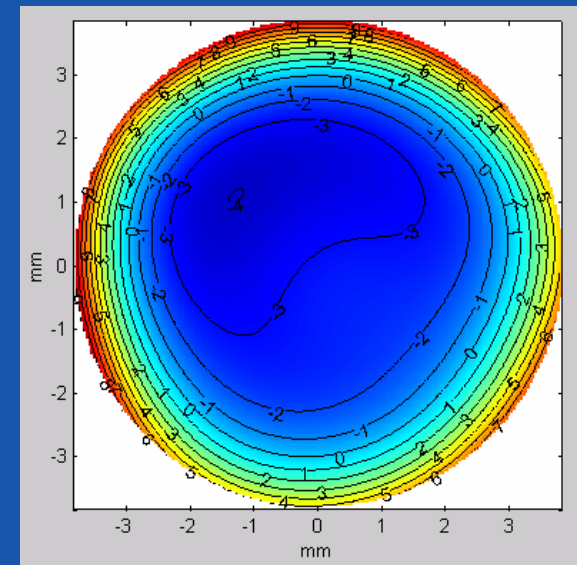
Hur påverkas synen?

Mörkerkörning

4°



4 mm pupil



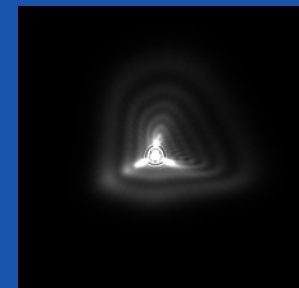
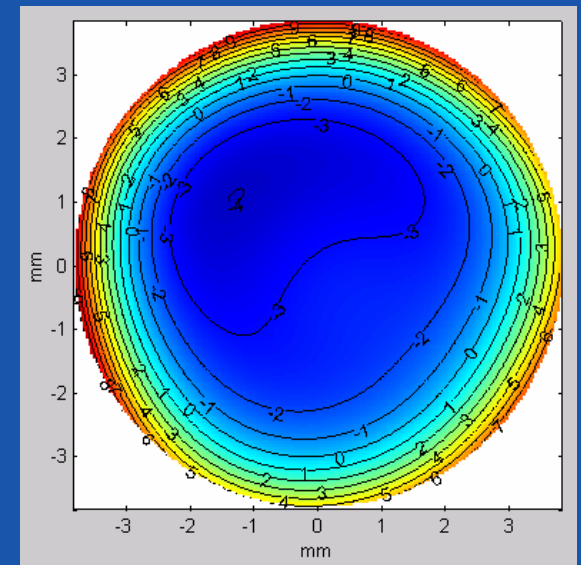
Hur påverkas synen?

Mörkerkörning

4°



6 mm pupil



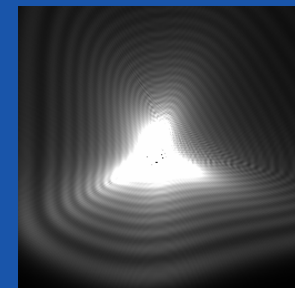
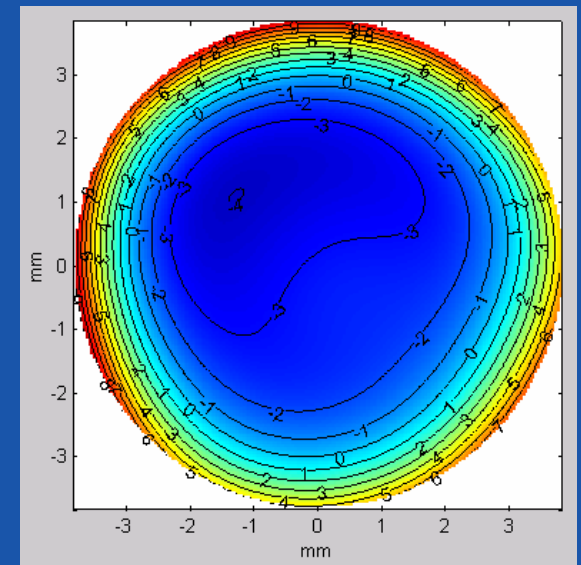
Hur påverkas synen?

Mörkerkörning

4°

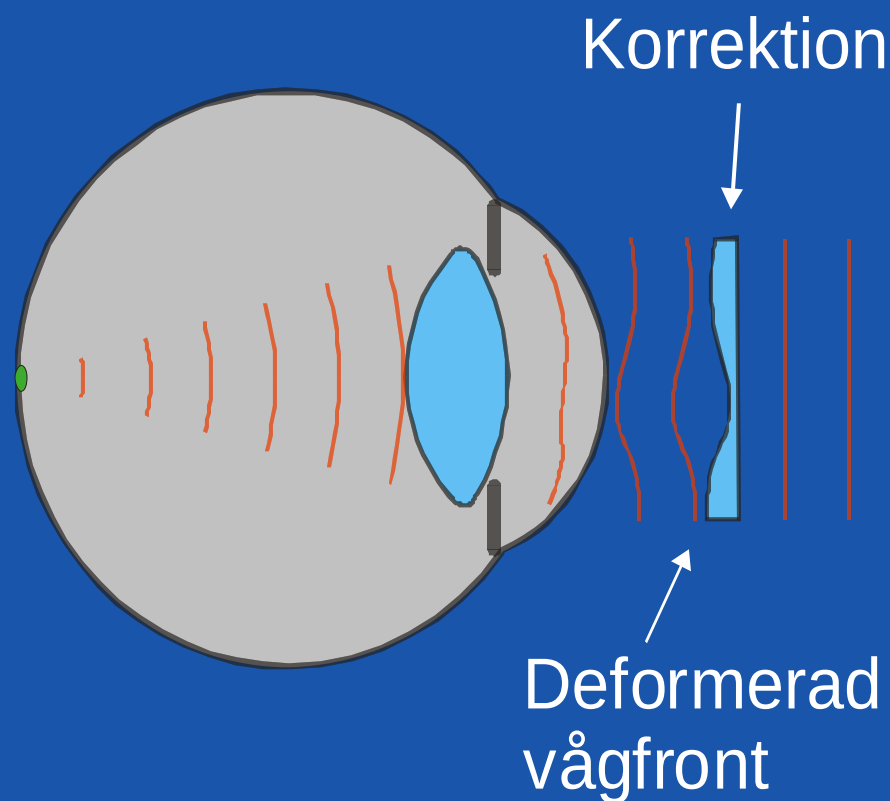


7,7 mm pupil

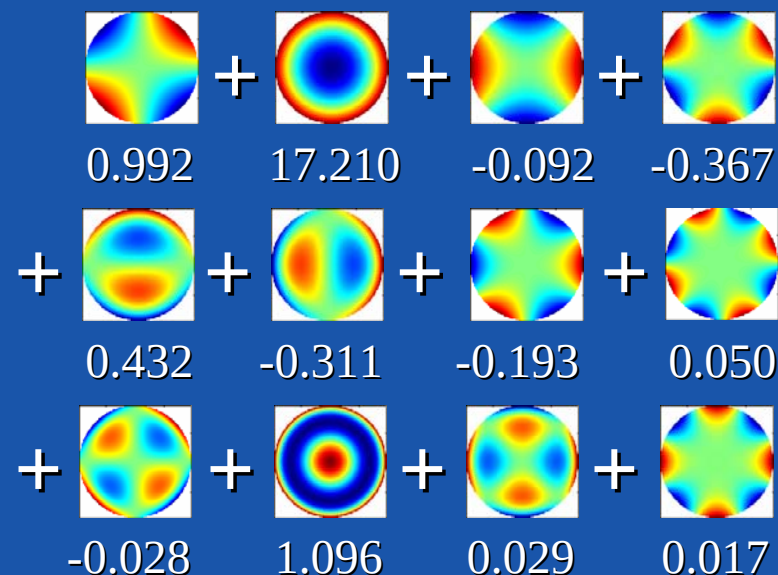


Aberrationskorrektur

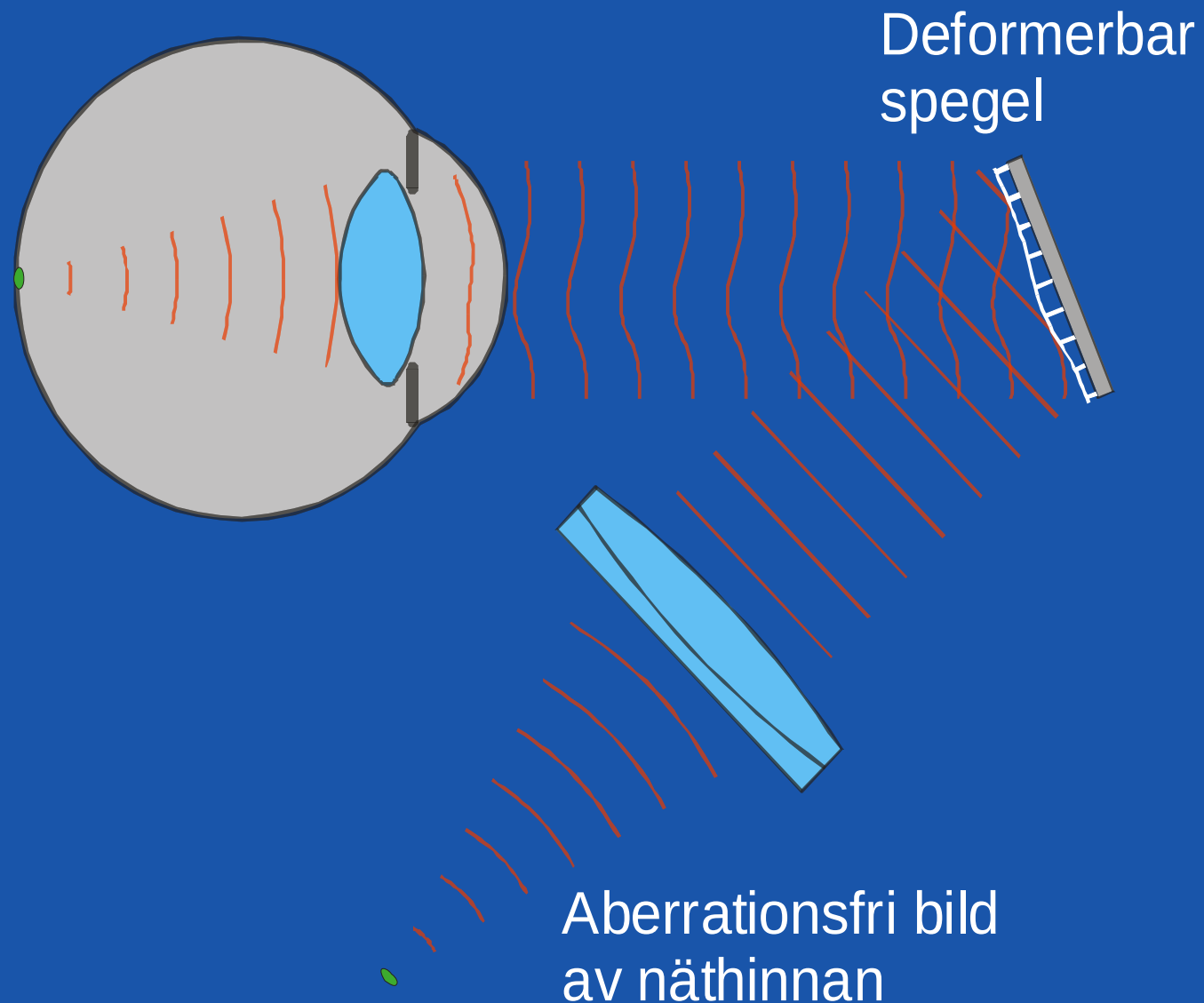
Vi behöver ett recept på korrekturen



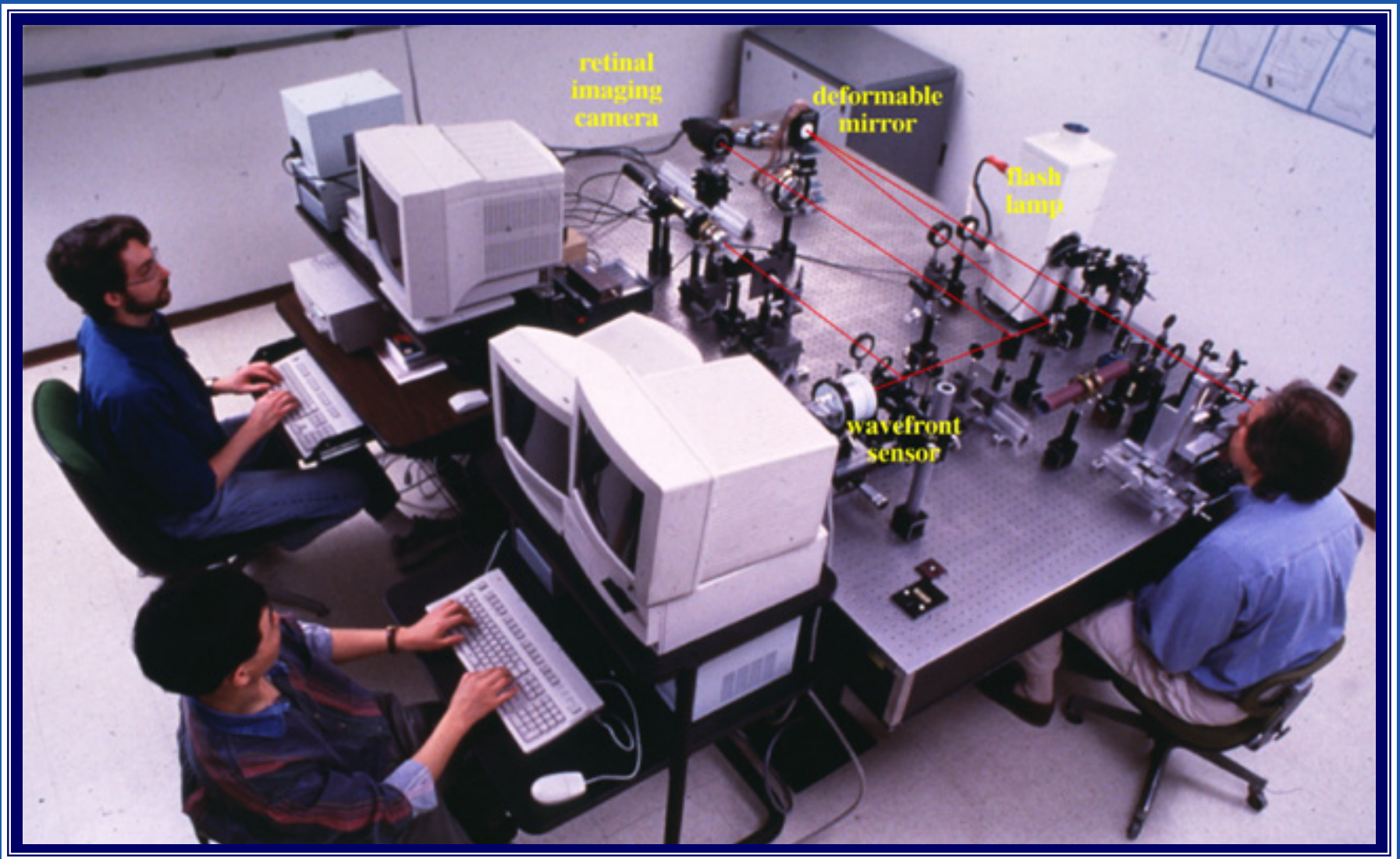
Recept = vågfront =
zernikekoefficienter!



Adaptiv optik (AO)

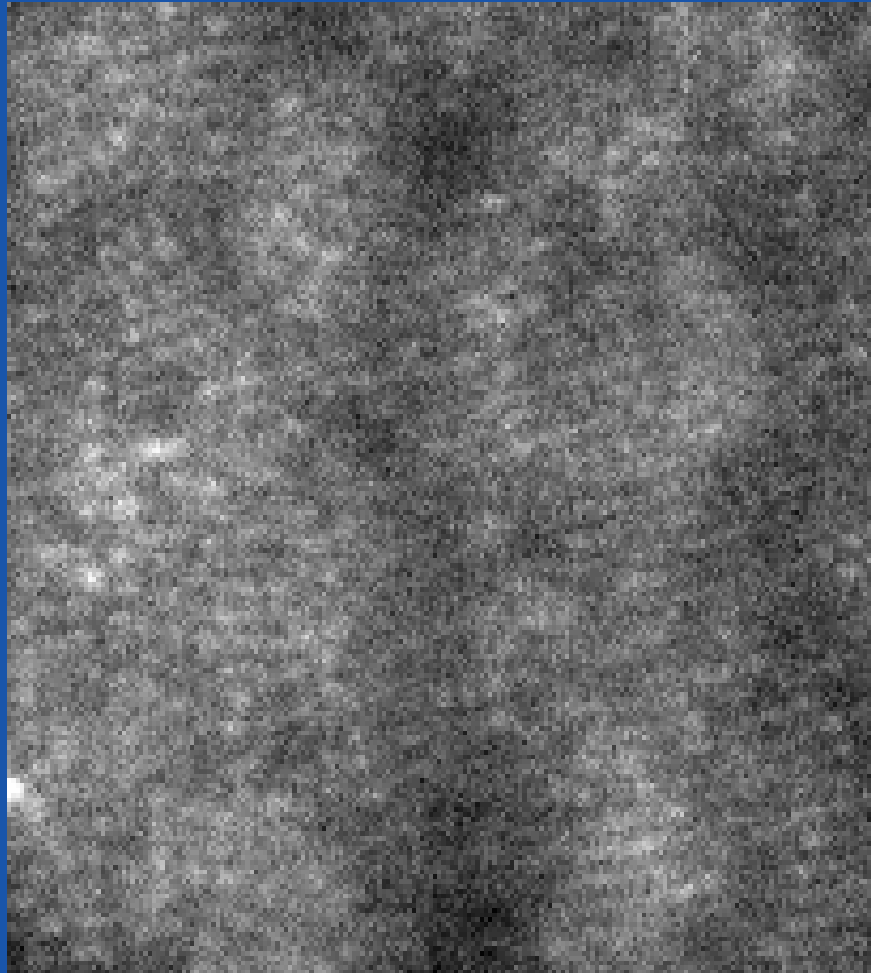


The Rochester Adaptive Optics Ophthalmoscope



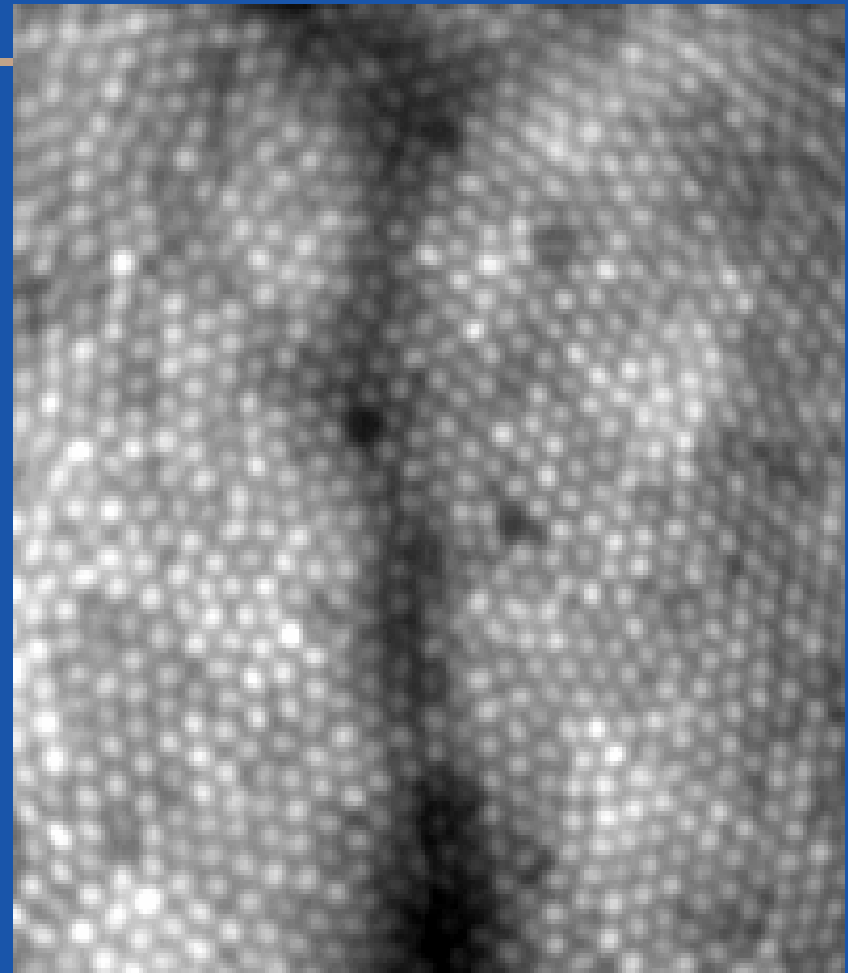
Med vänligt tillstånd av Austin Roorda

Utan adaptiv optik



*JW right eye
1 deg eccentricity
image wavelength = 550 nm
April 21, 1997*

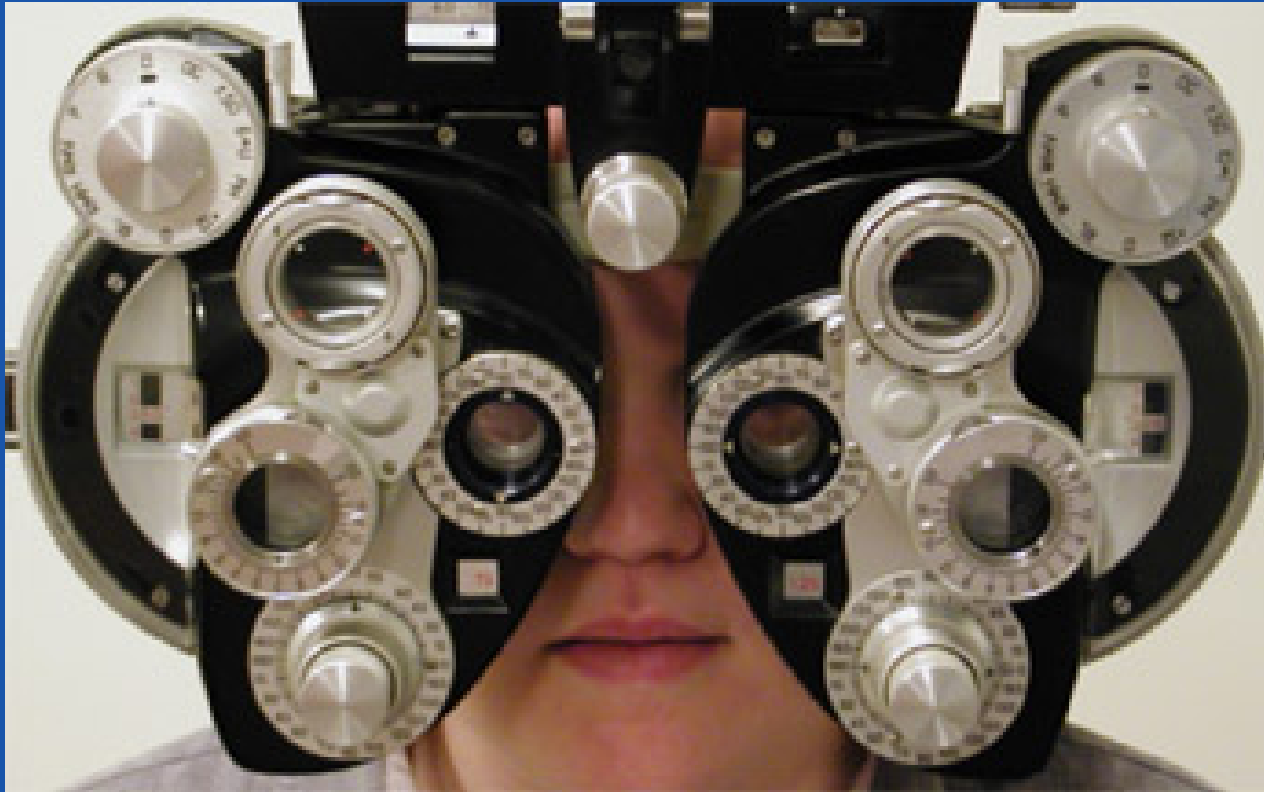
Med adaptiv optik



10 arc min
(48.6 μ m)

Med vänligt tillstånd av
Austin Roorda

Adaptiv optik

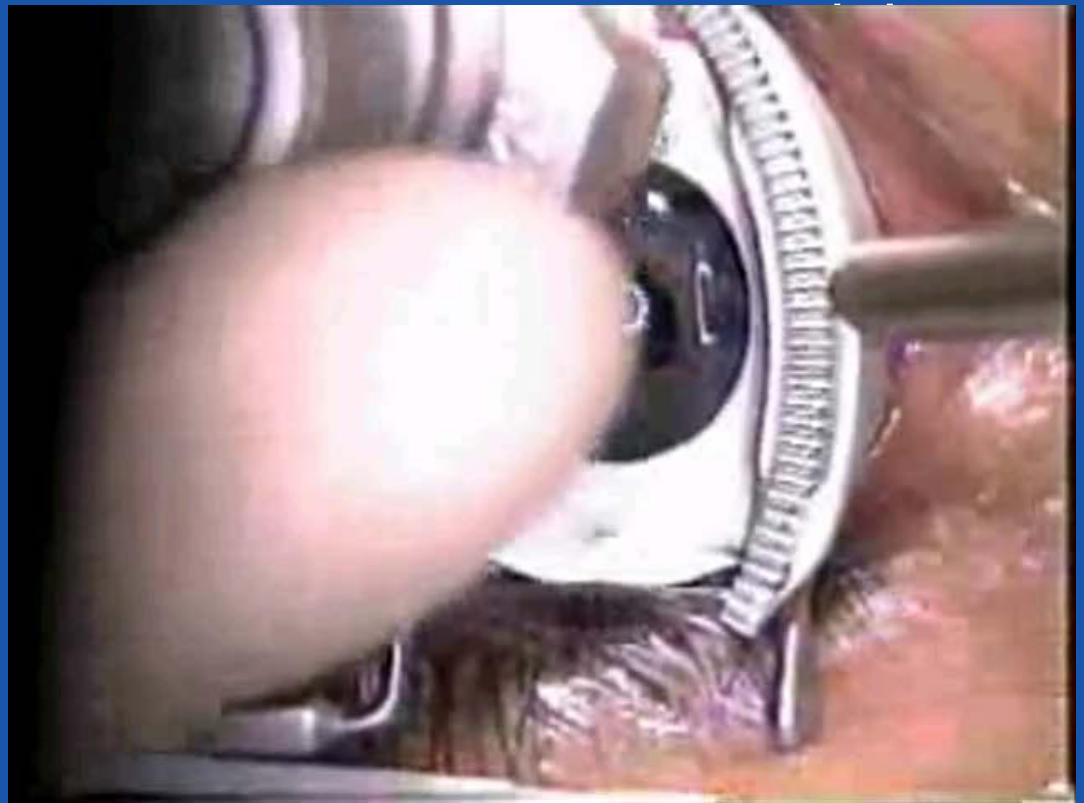


Coming soon....

Sätt att minska ögats aberrationer

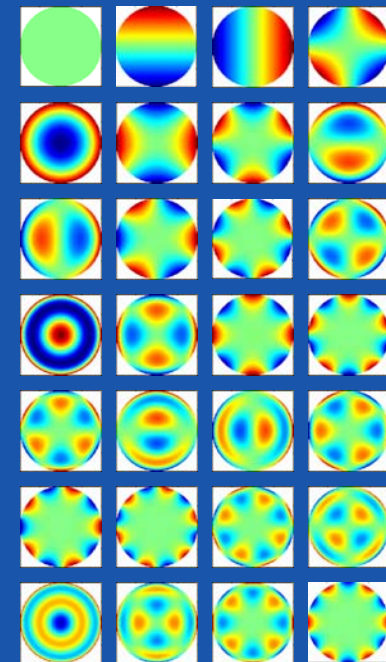
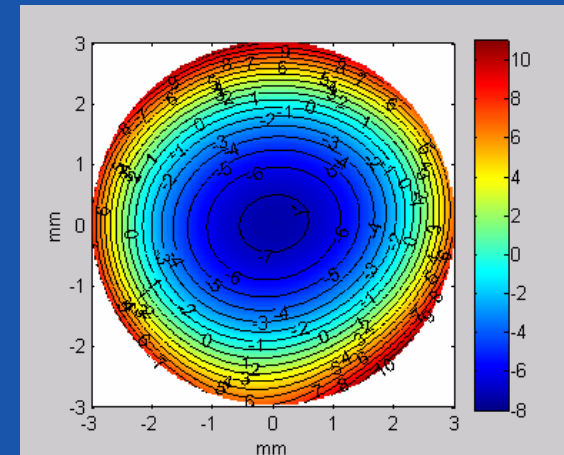
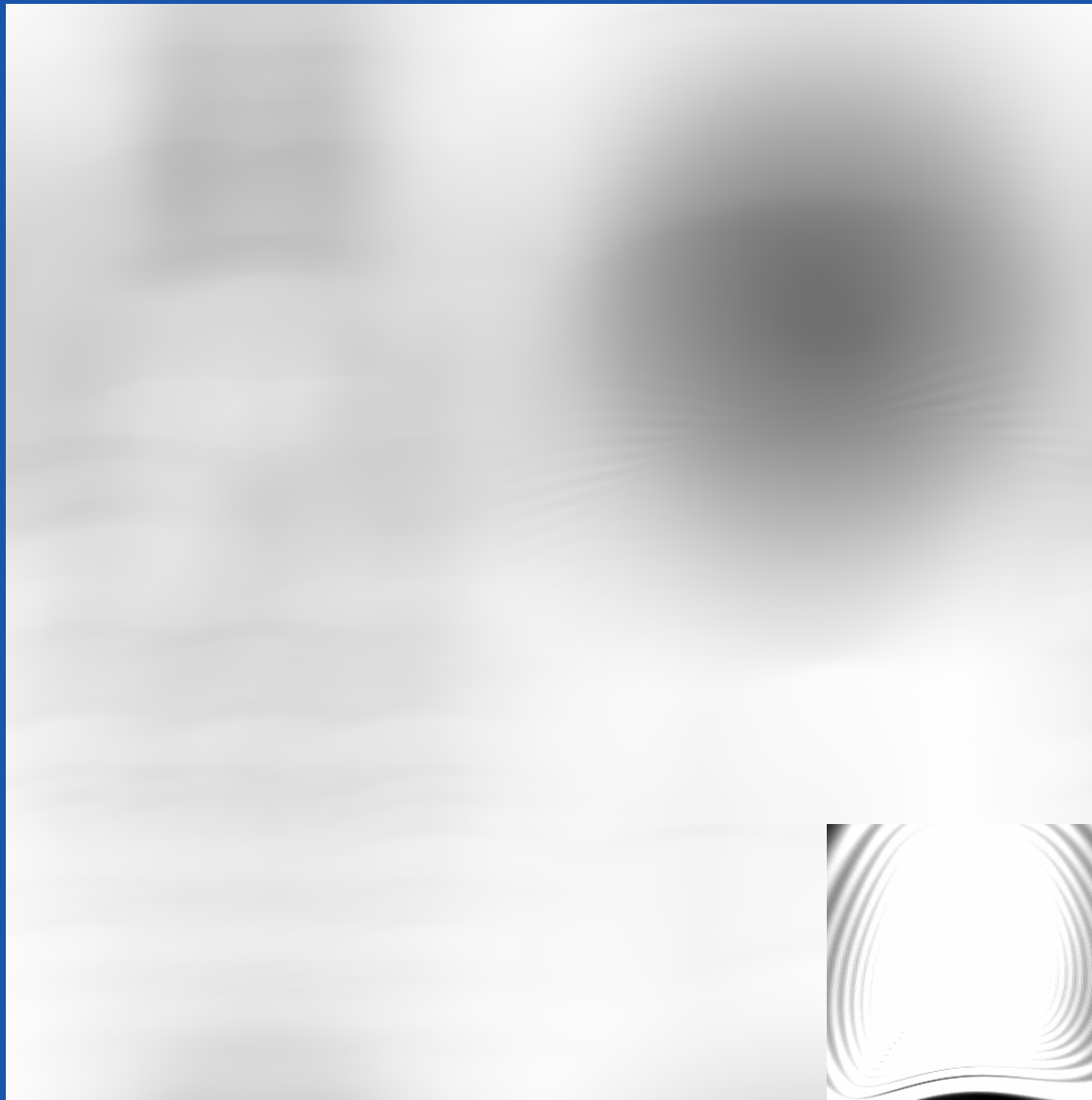
Vågfront = Recept

- Laserkirurgi
- Kontaktlinser
- Intraokulärlinser
- (Glasögon)



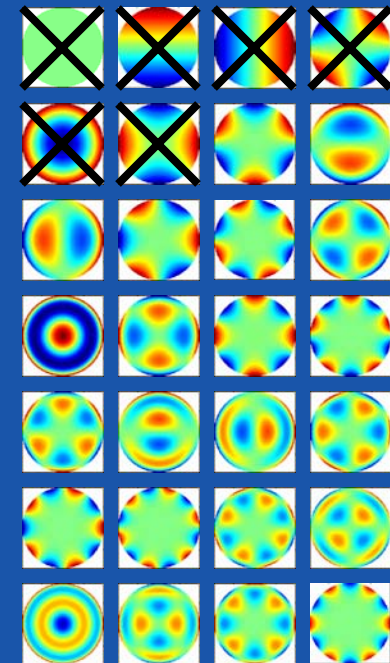
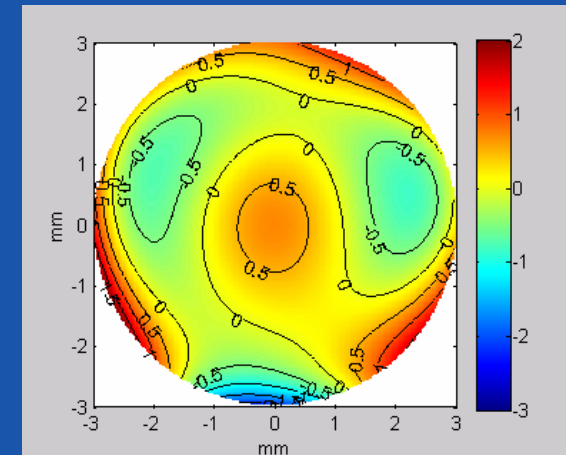
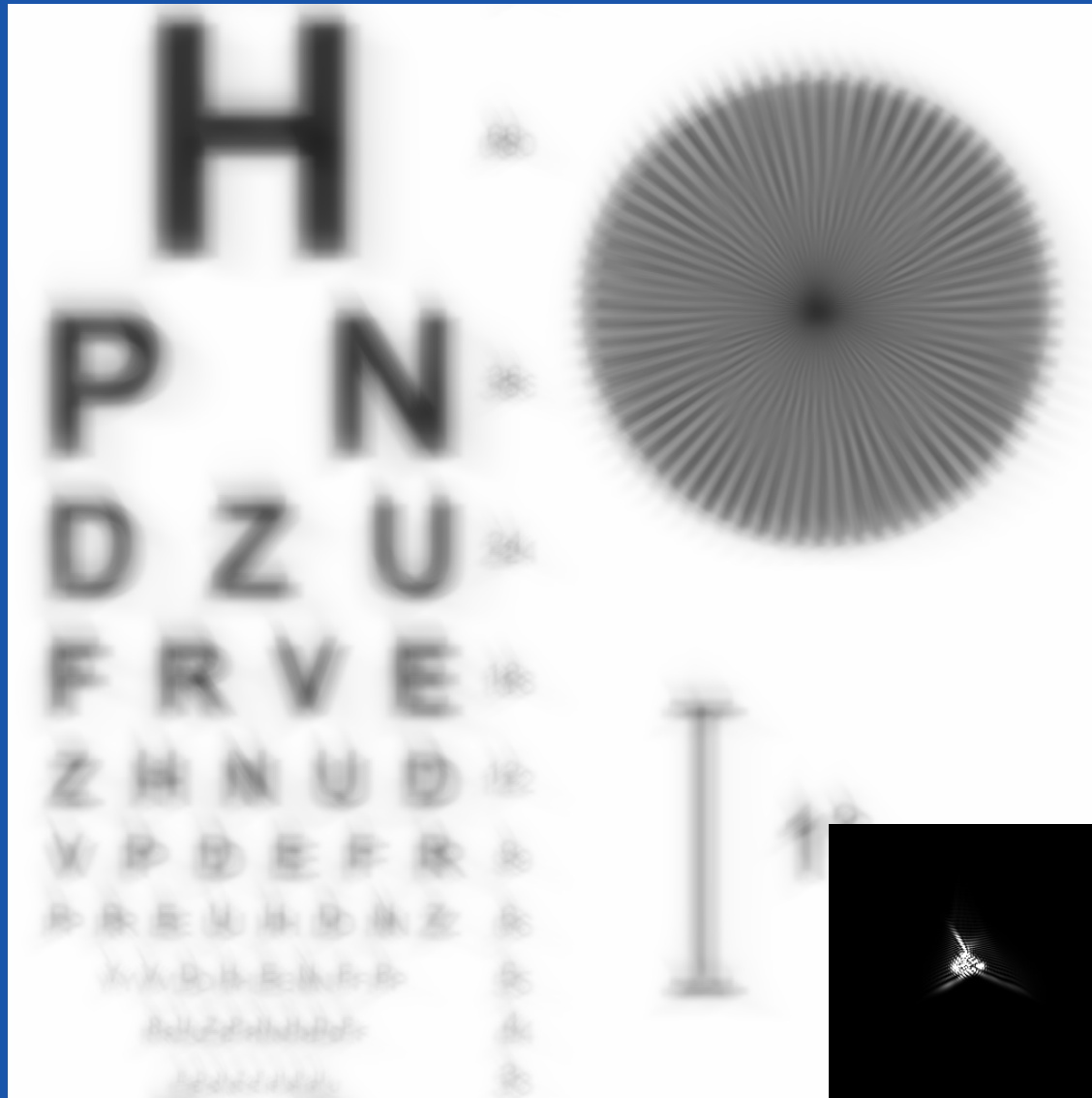
Okorr. öga (-3, -0.75, 10°, 6 mm pupill, RMS = 0.5 μm)

4°



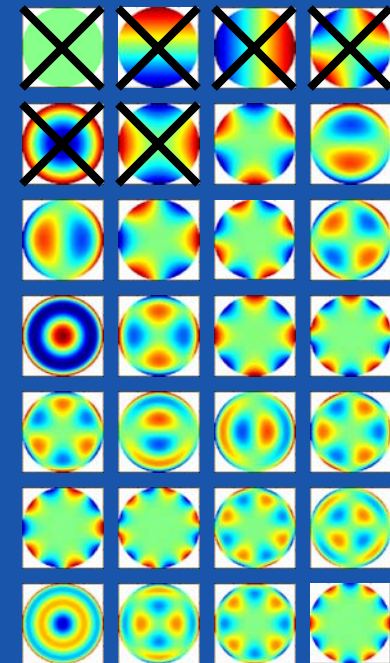
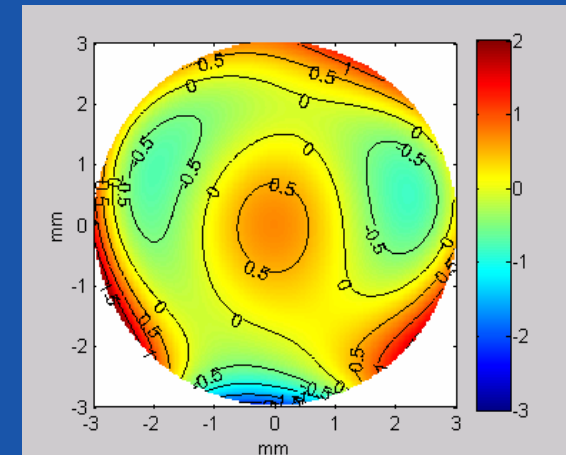
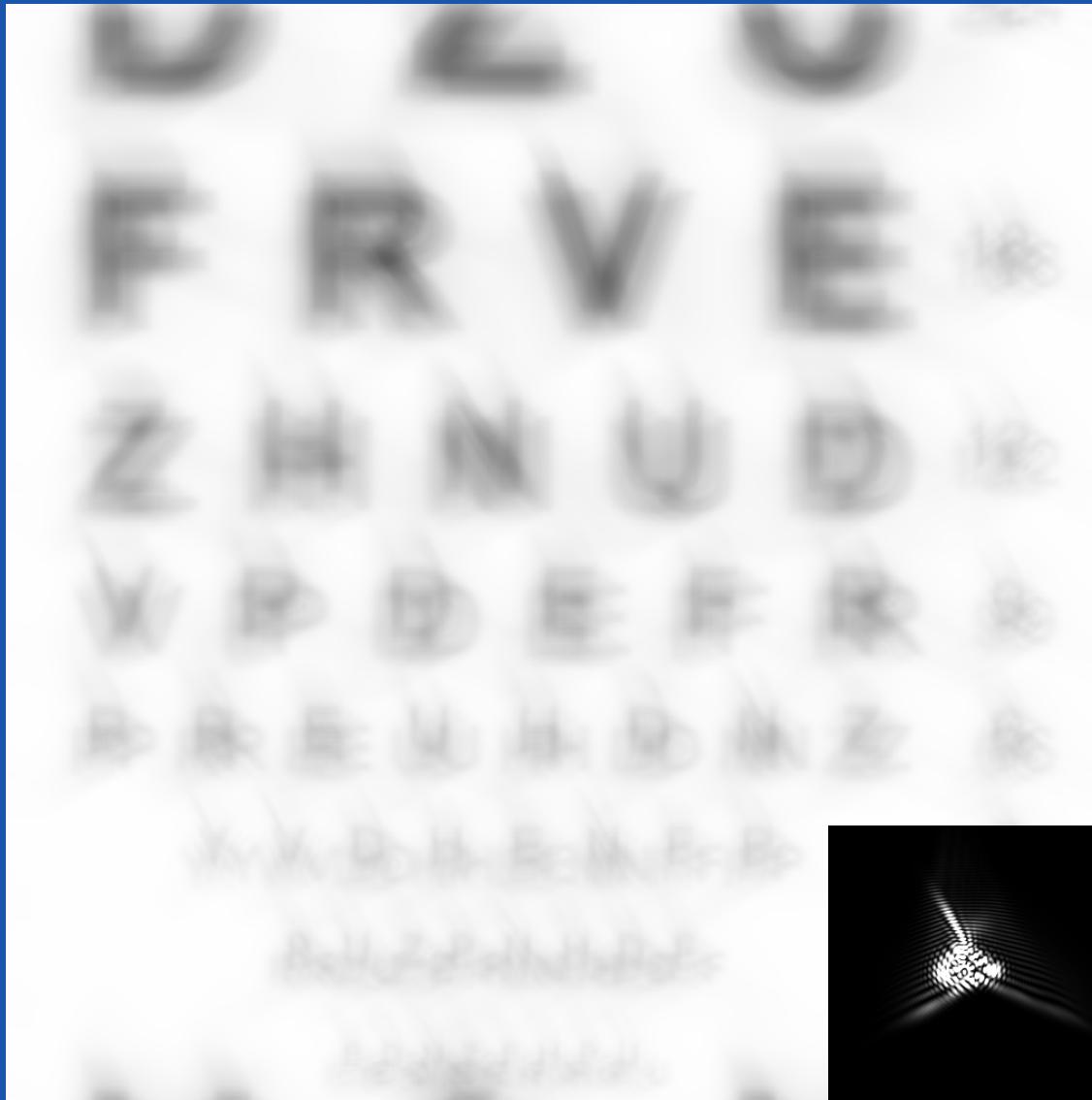
Sfär +cyl korrektion

4°



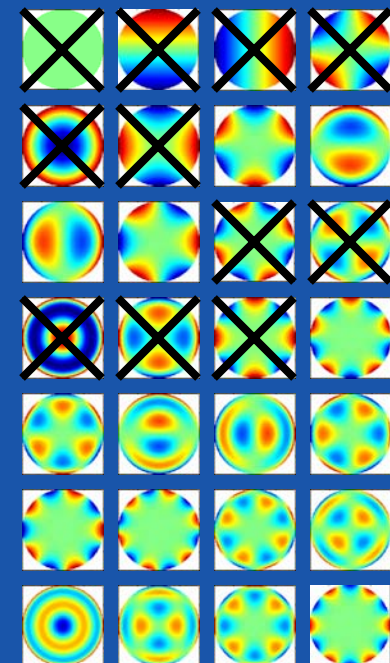
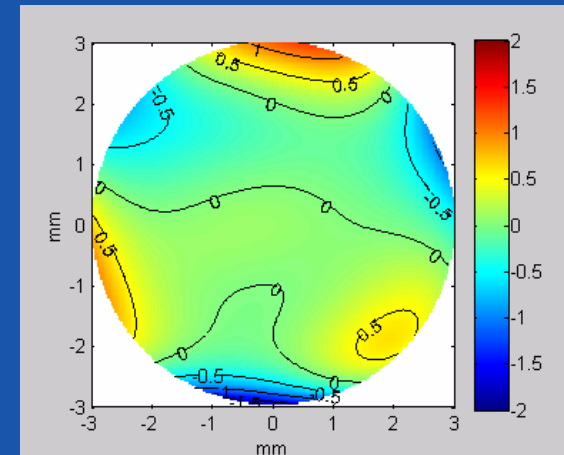
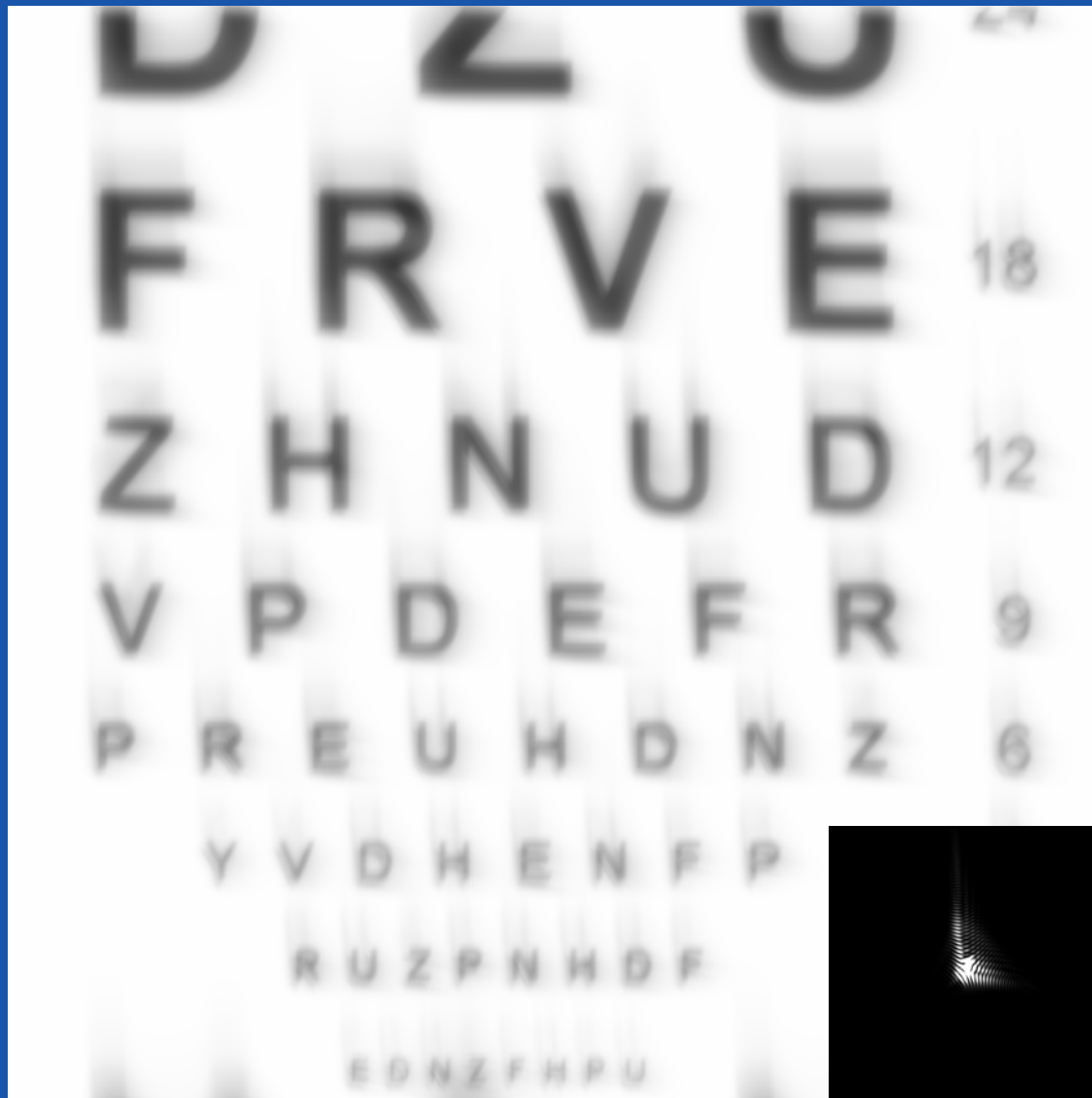
Sfär +cyl korrektion

2°

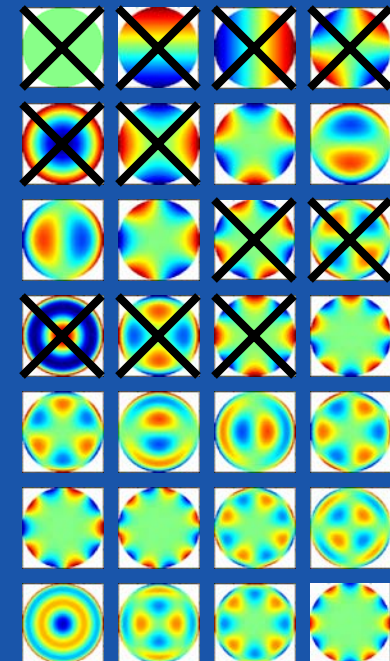
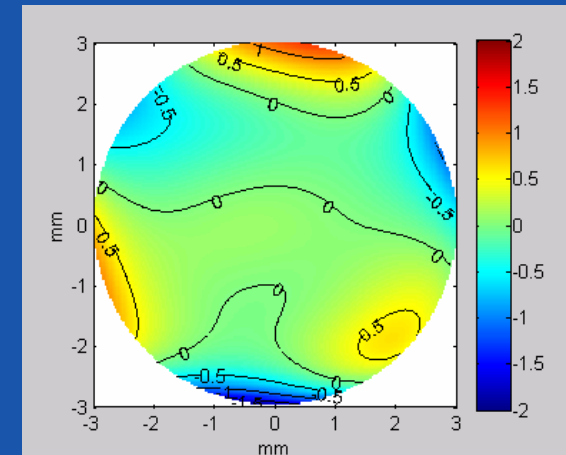
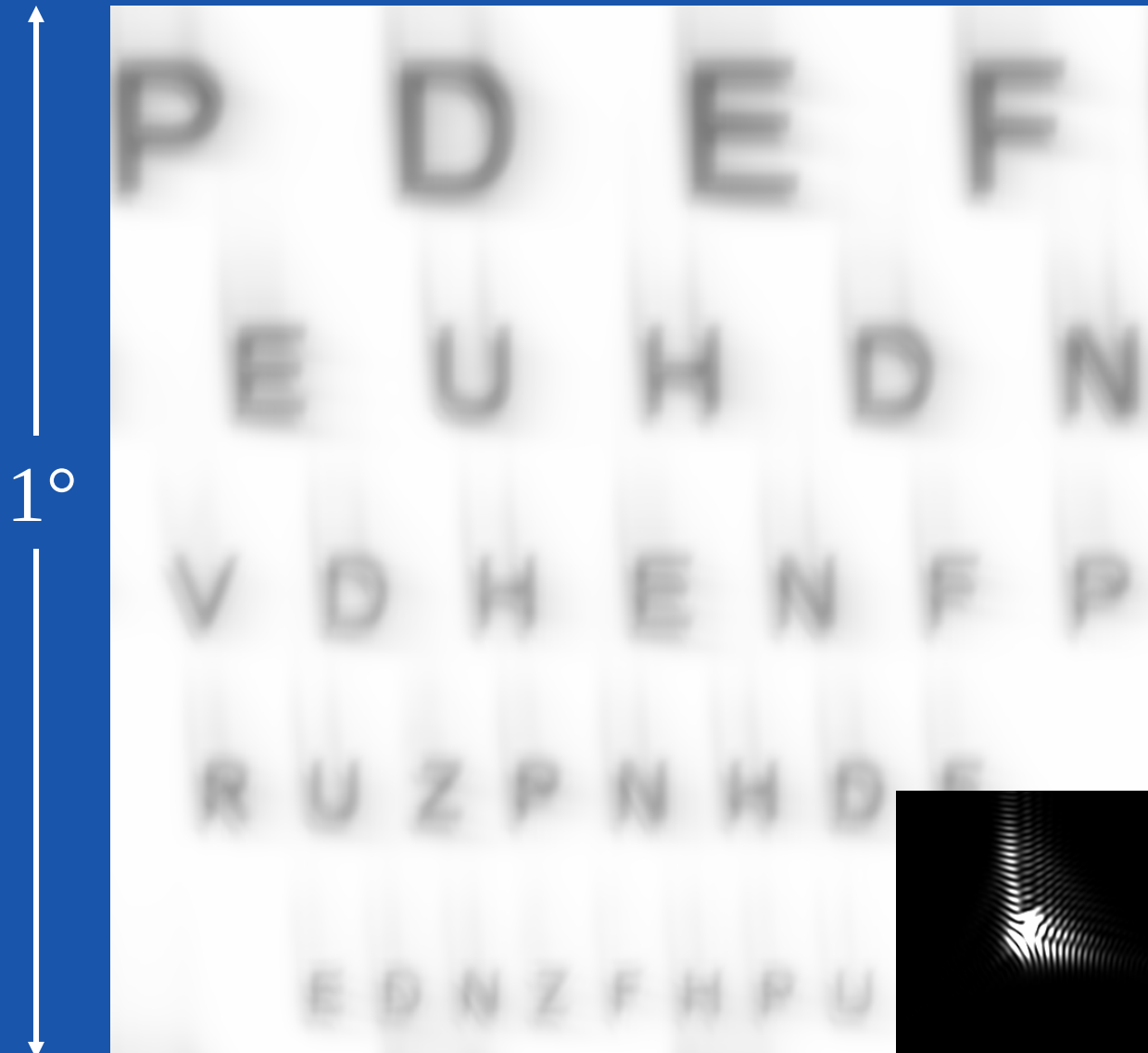


Sf+cyl+sf ab korrektion

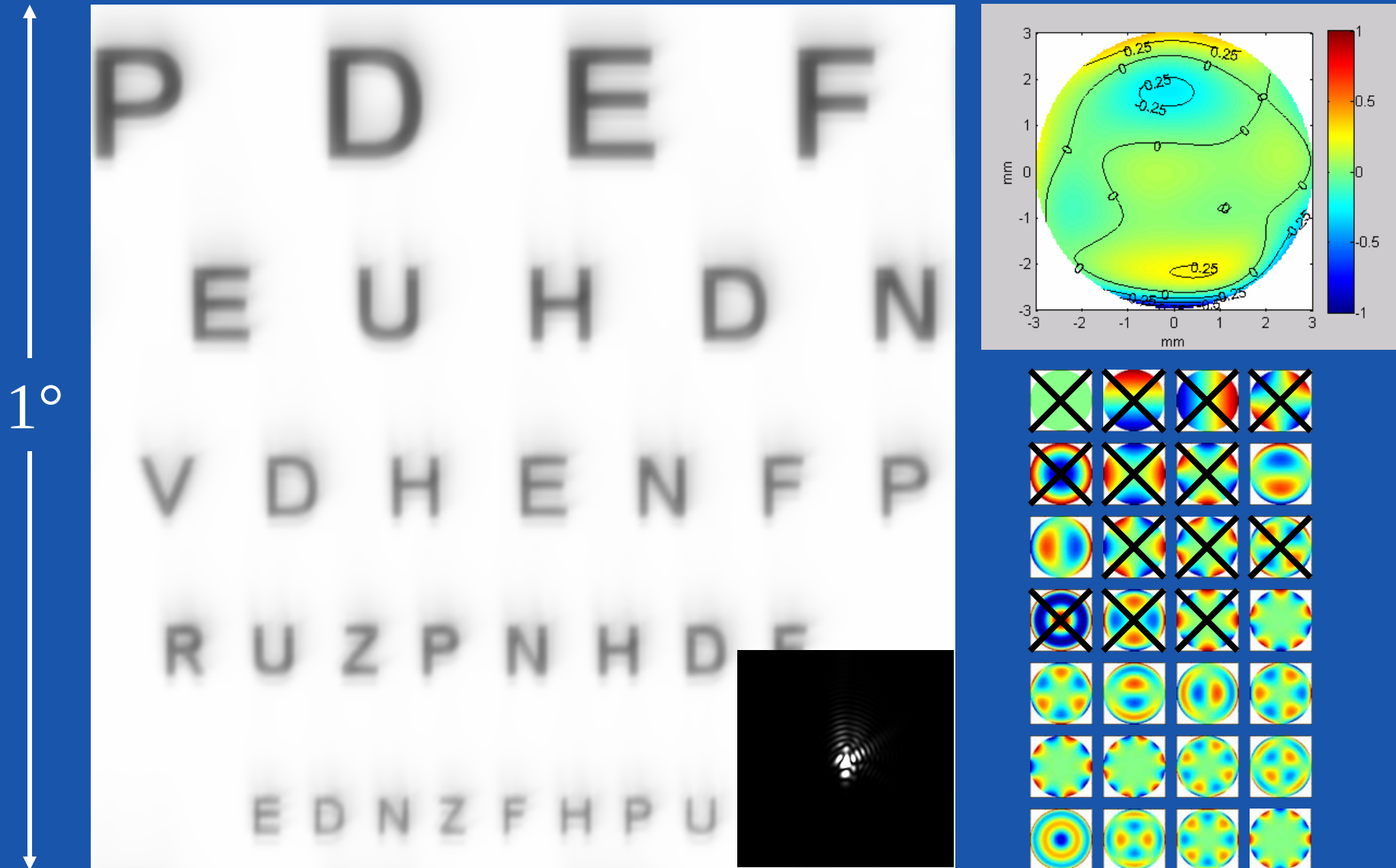
2°



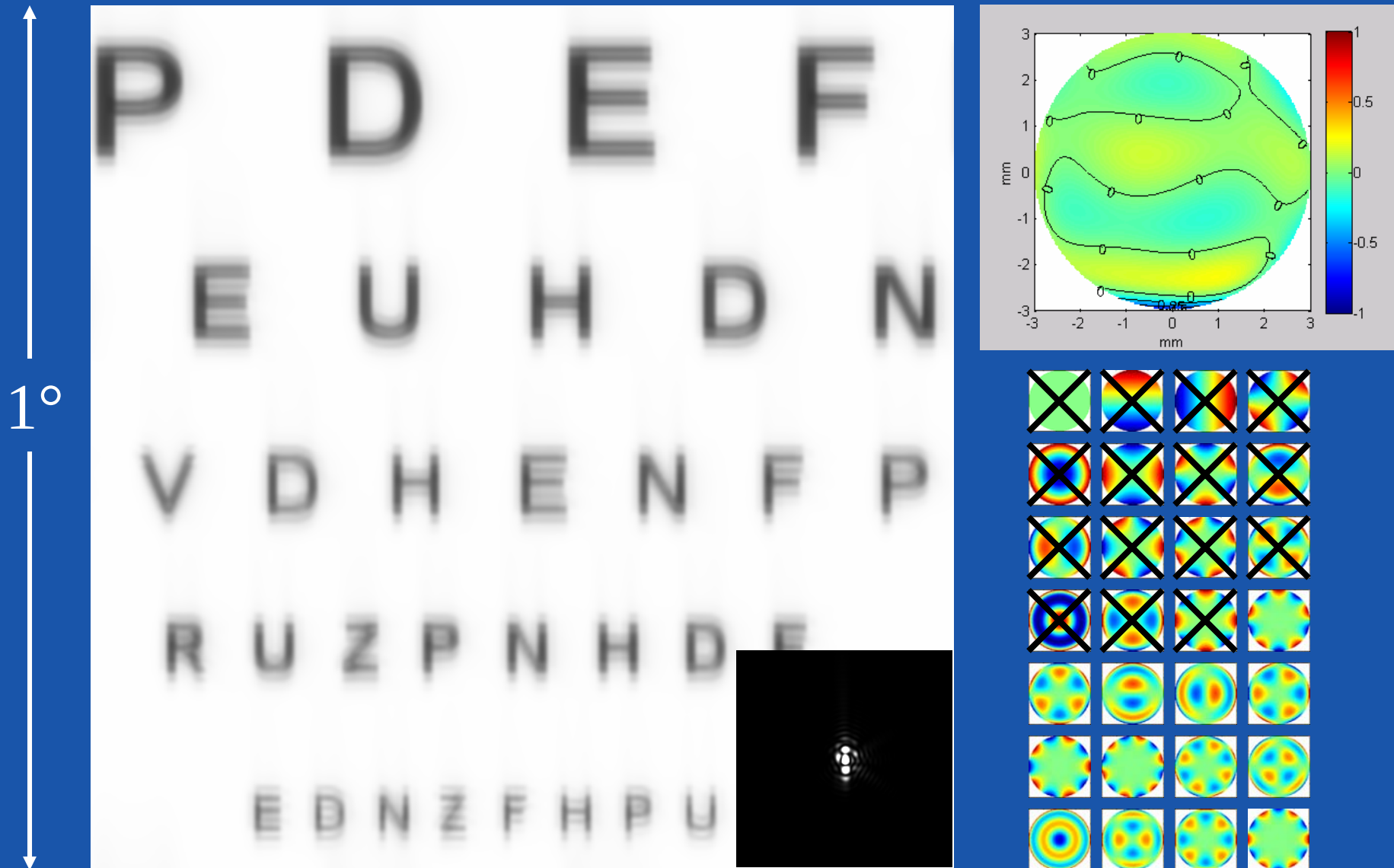
Sf+cyl+sf ab korrektion



Sf+cyl+sf ab+trefoil korrektion

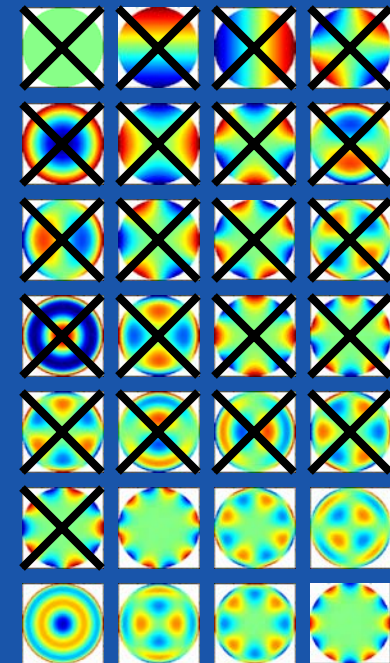
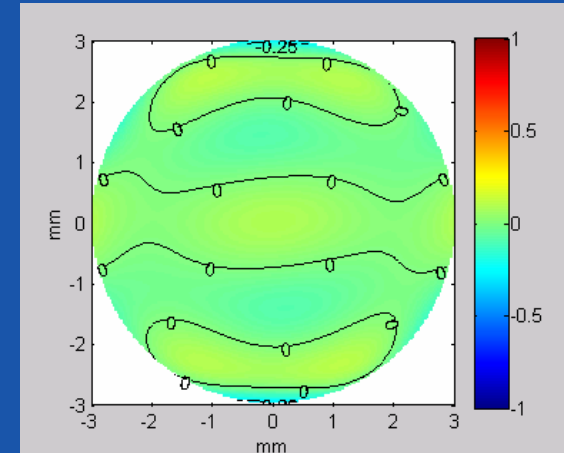
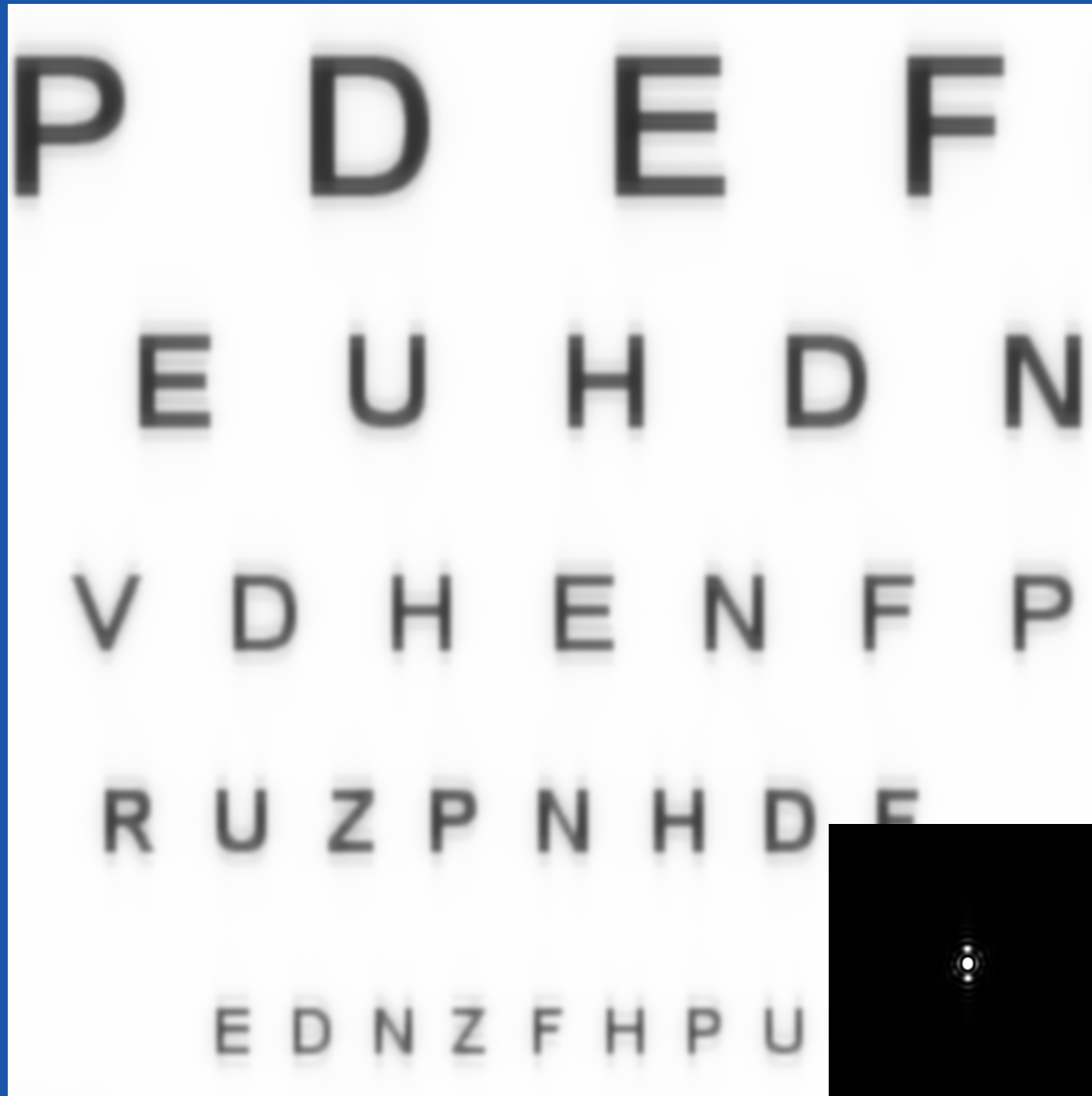


Sf+cyl+sf ab+tref+koma korrektion

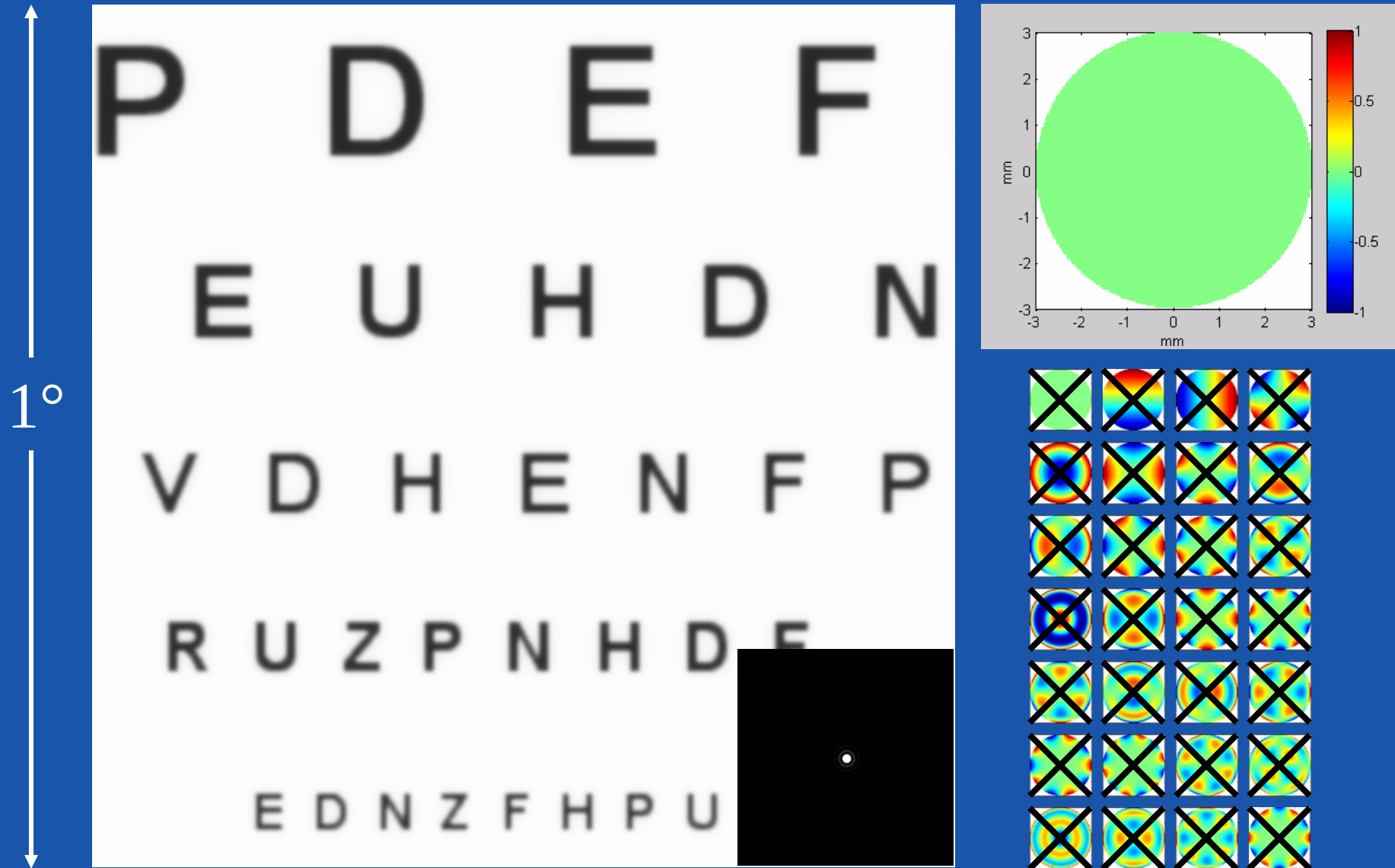


Sf+cyl+sf ab+tref+koma+sek koma korrektion

1°

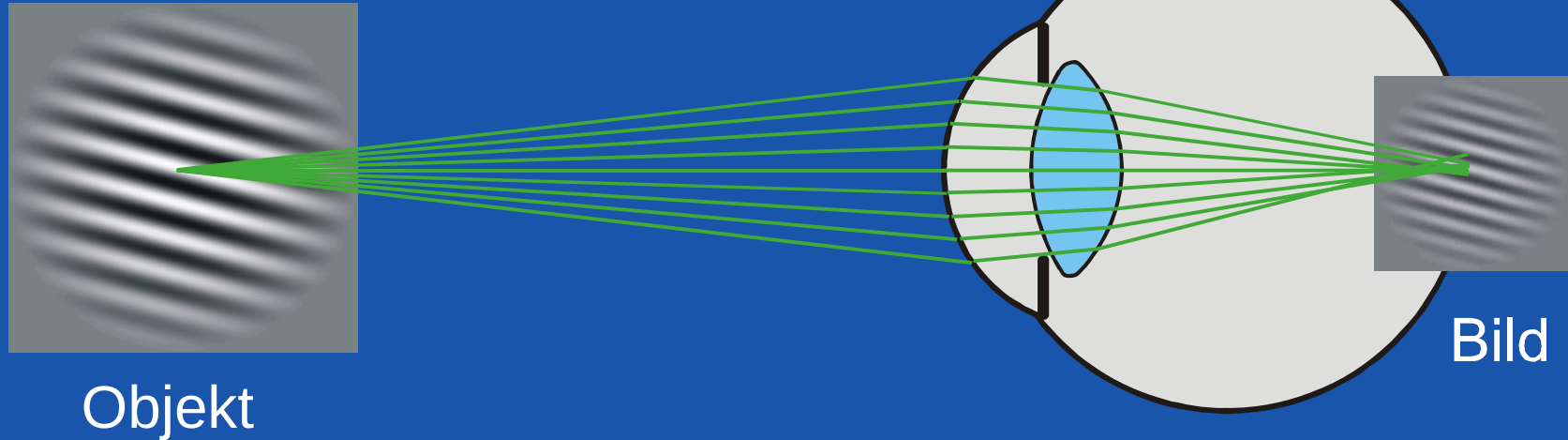


Fullständig korrektion



MTF

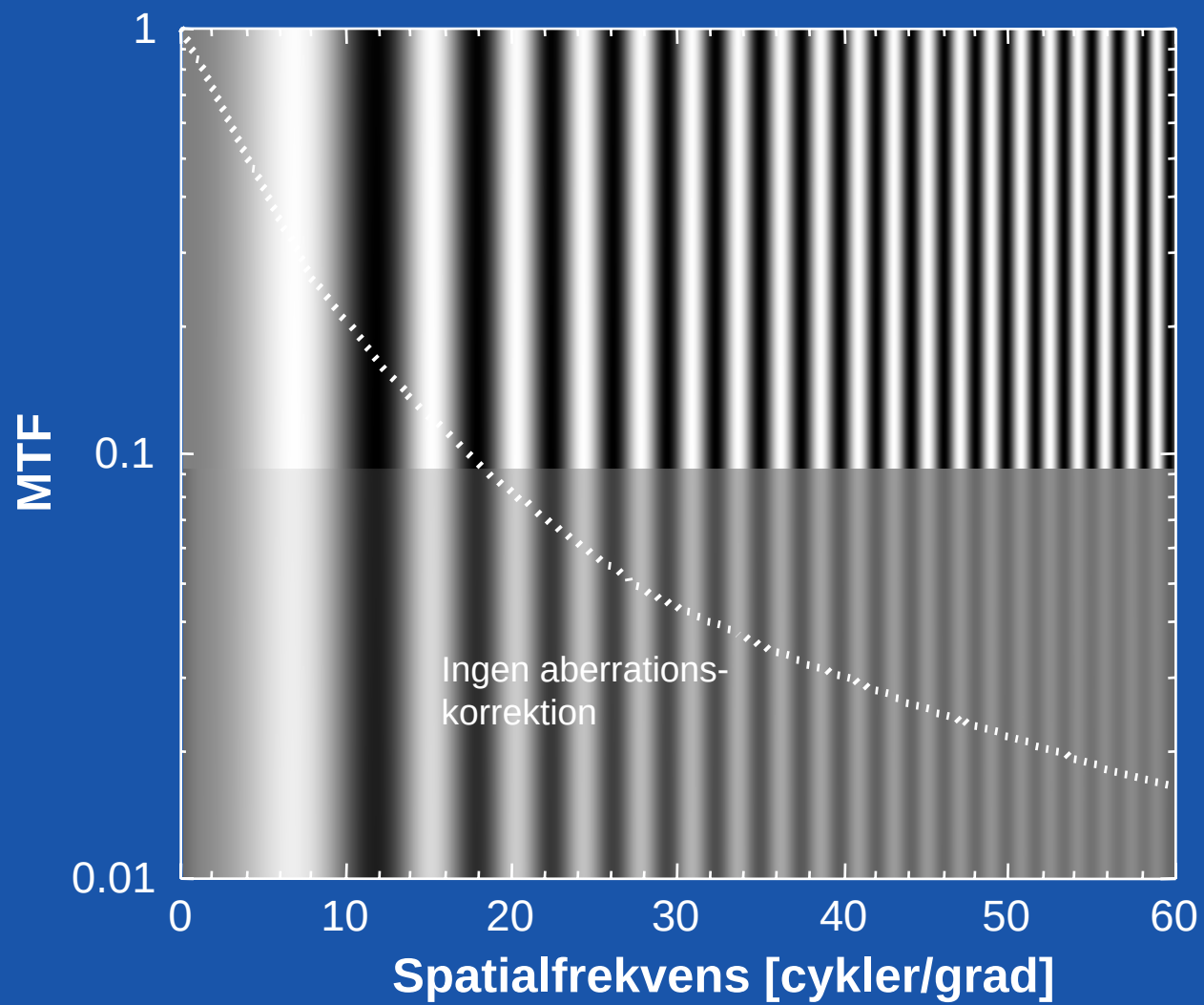
Viss bildkvalitet



$$MTF = \frac{\text{Kontrast i bild}}{\text{Kontrast i objekt}}$$

$$0 \leq MTF \leq 1$$

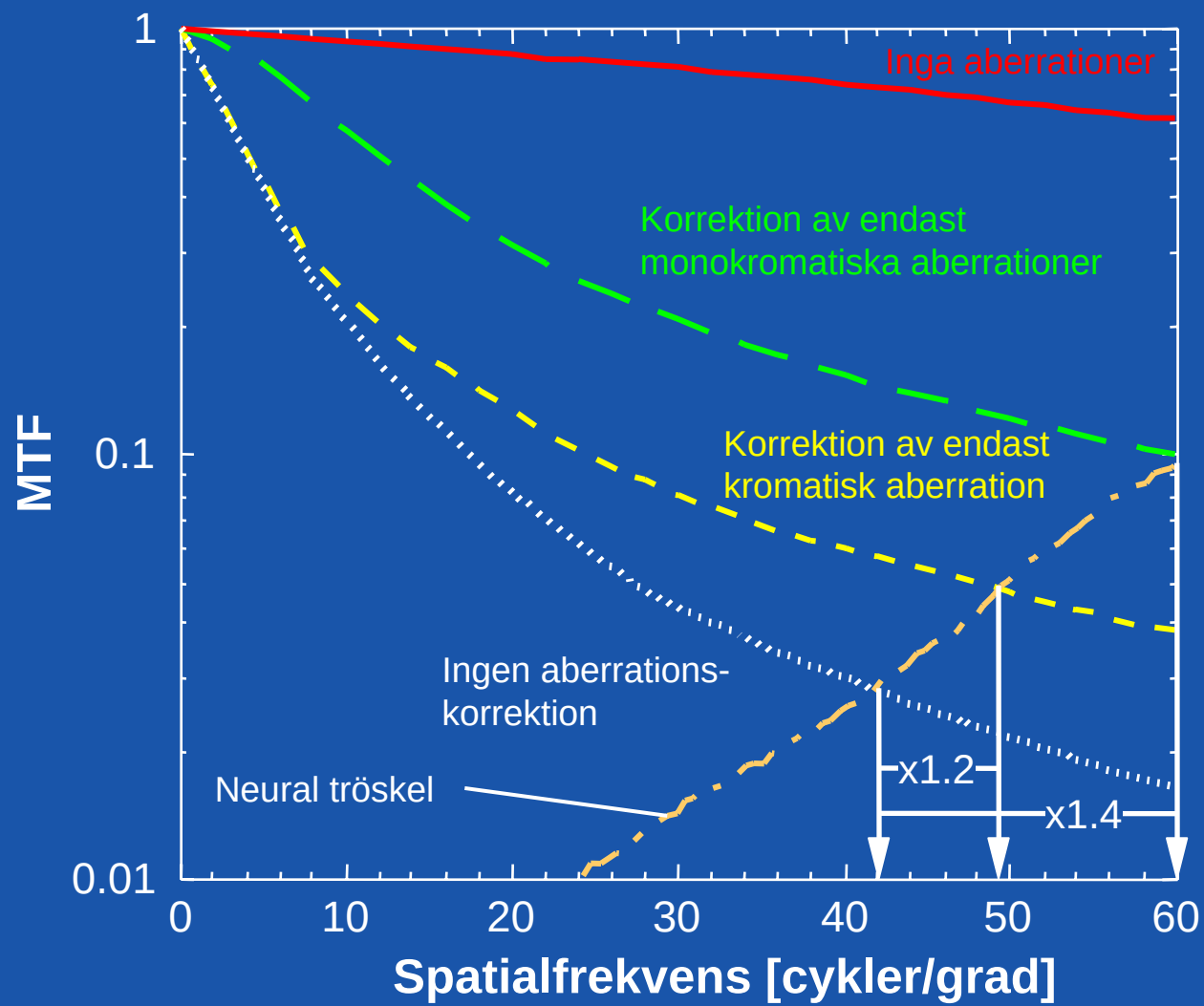
MTF



Objekt

Bild

MTF



Begränsande faktorer för ”supersyn”

- Tappavståndet i fovea
- Kromatisk aberration
- Spridning
- Dynamiska förändringar i ögat
- Ackommodation
- Förändringar i linsen



110 cykl/grad