

Wavefront
Sensing in the
Human Eye

Austin Roorda

Point Spread Function vs. Pupil Size

1 mm

2 mm

3 mm

4 mm

5 mm

6 mm

7 mm

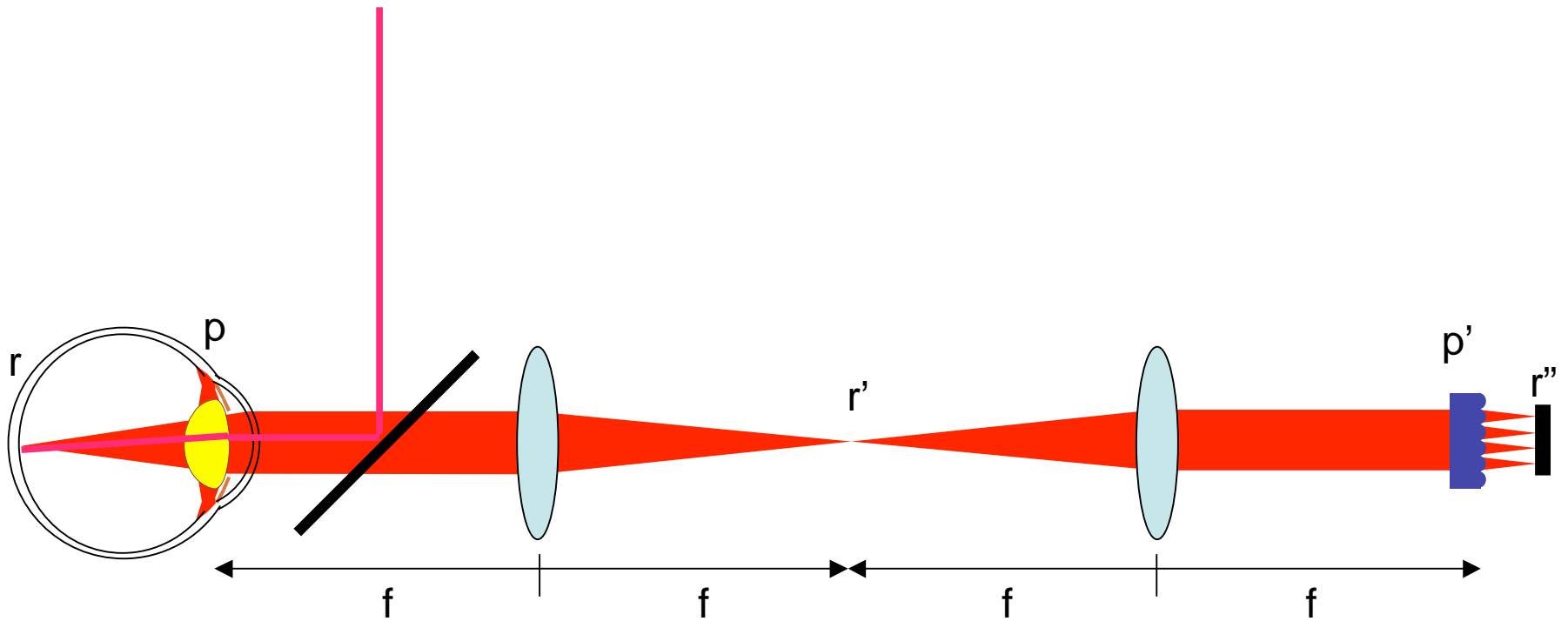


Perfect Eye

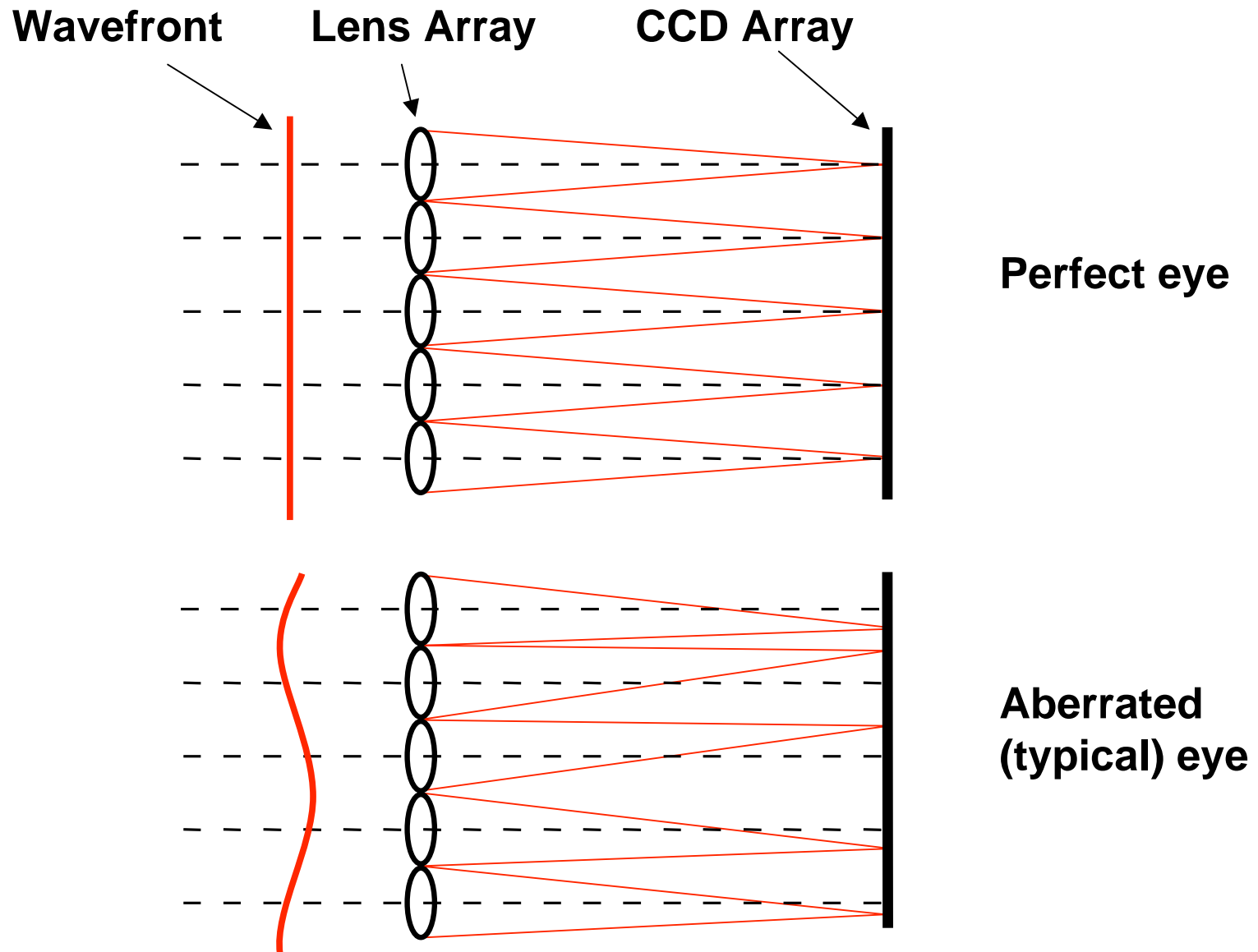


Typical Eye

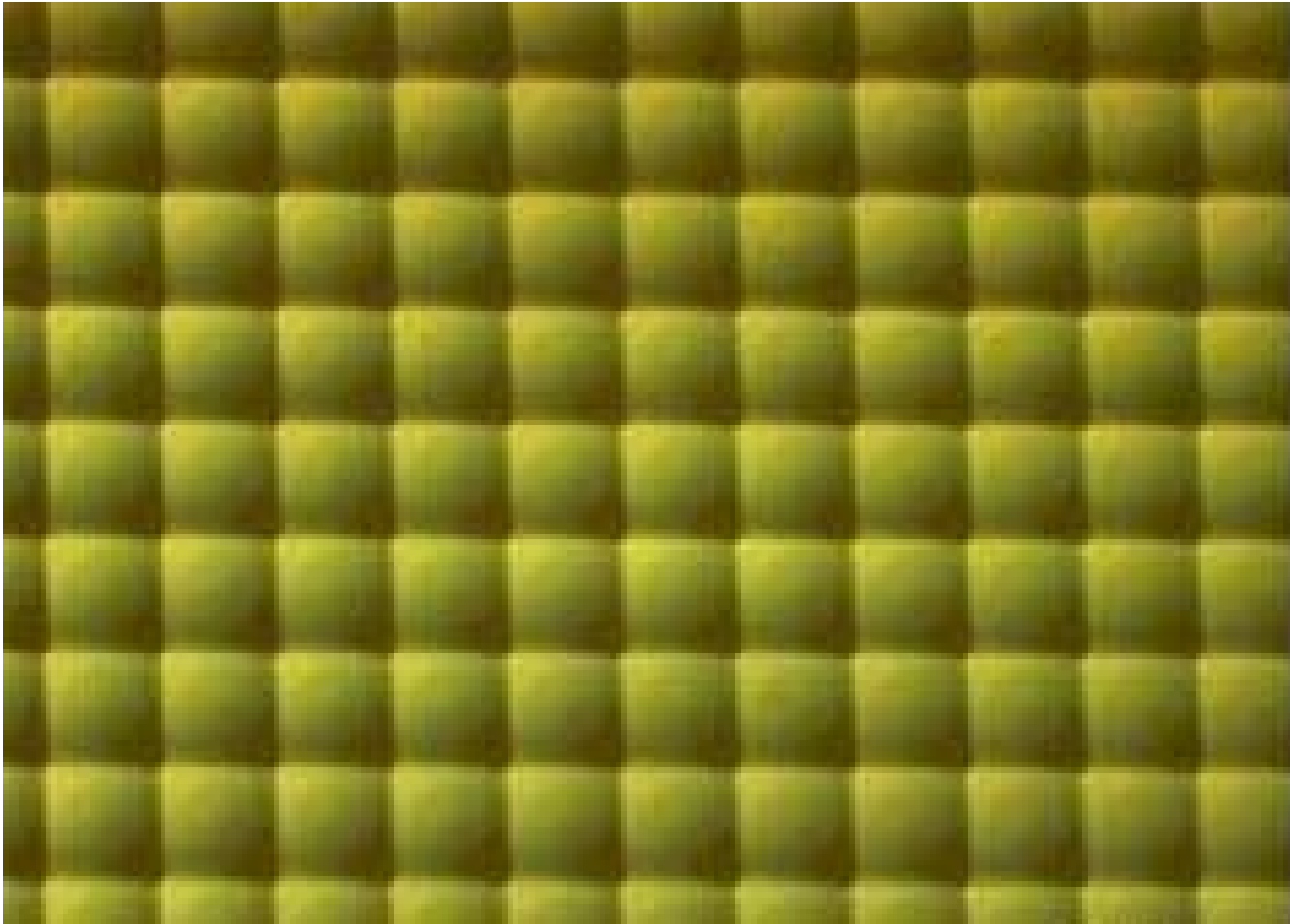
Shack Hartman Wavefront Sensor



Hartmann-Shack Wavefront Sencsc

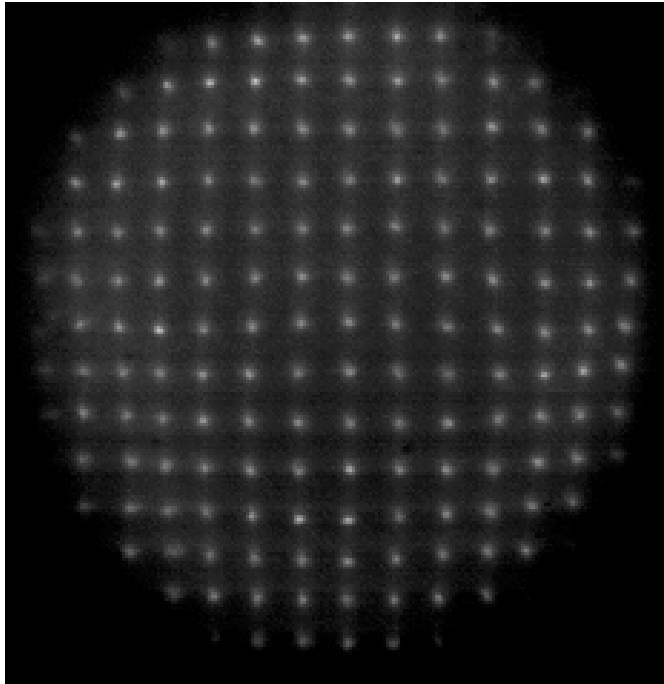


Lenslet Array

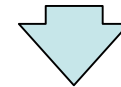


Typical values 200 - 400 micrometer diameter
 7 to 25 mm focal length

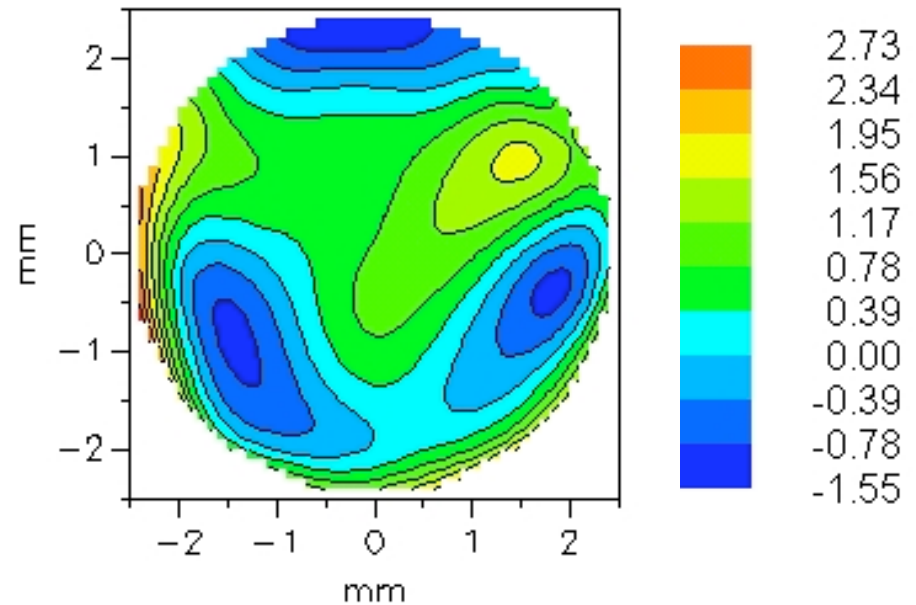
Wavefront sensor image



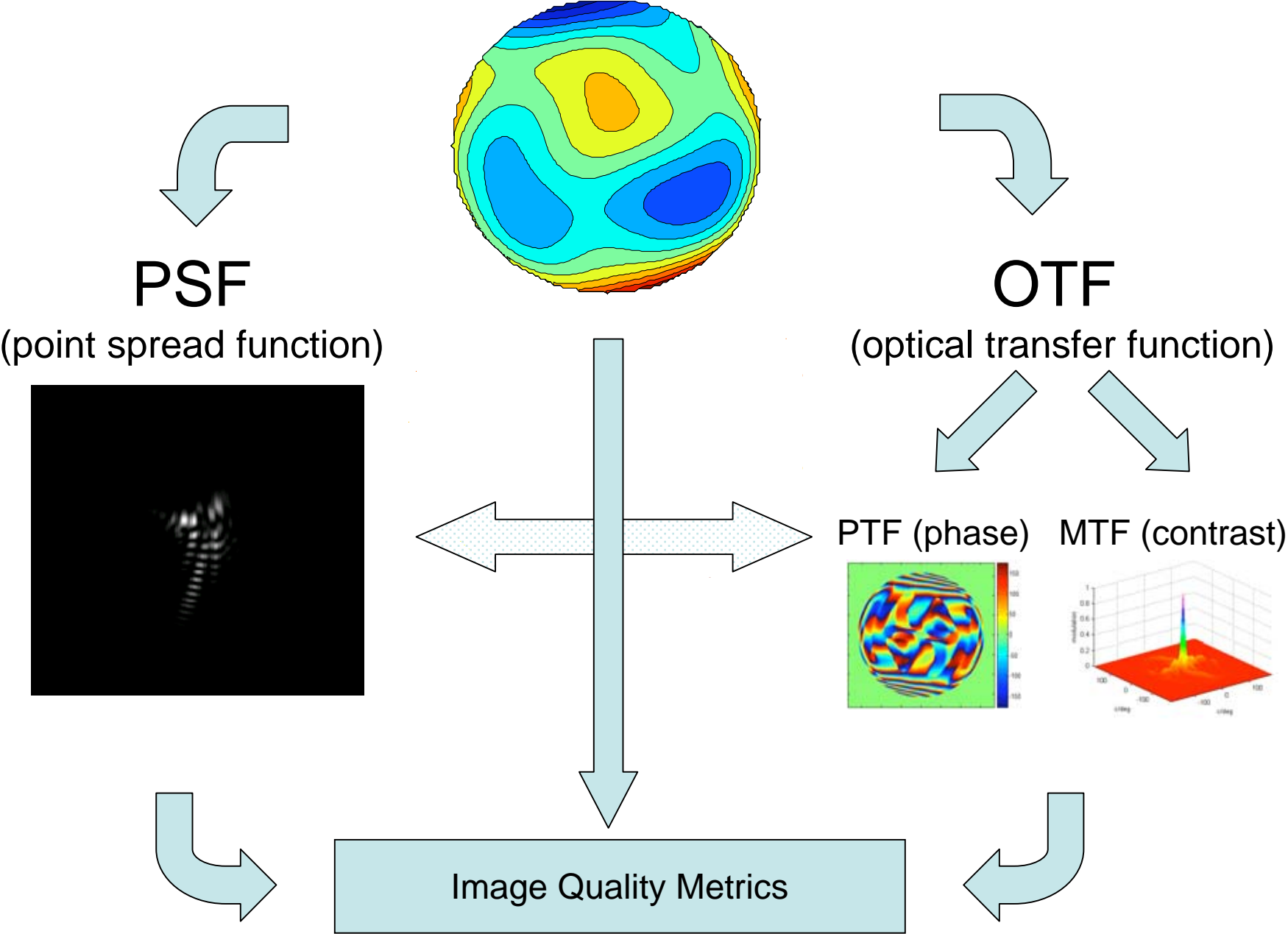
Convert slope data to
wavefront height data



Wavefront Map
(height in microns)



The reason we measure the wave aberration



The PSF is the Fourier Transform (FT) of the pupil function

$$h(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(u, v) e^{-i2\pi(ux + vy)} du dv$$

The MTF is the amplitude component of the FT of the PSF

$$|H(f_x, f_y)| = \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x, y) e^{-i2\pi(f_x x + f_y y)} dx dy \right|$$

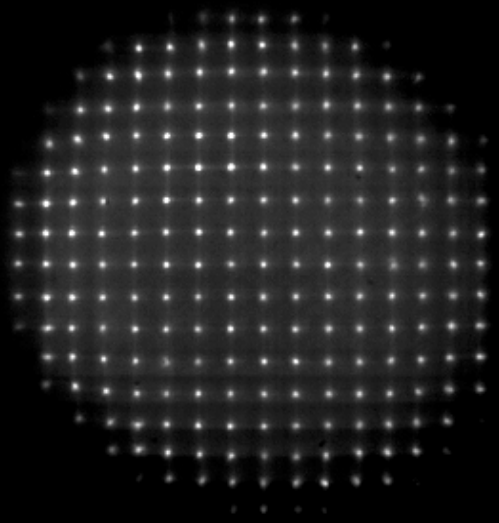
The PTF is the phase component of the FT of the PSF

$$\angle H(f_x, f_y) = \angle \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x, y) e^{-i2\pi(f_x x + f_y y)} dx dy$$

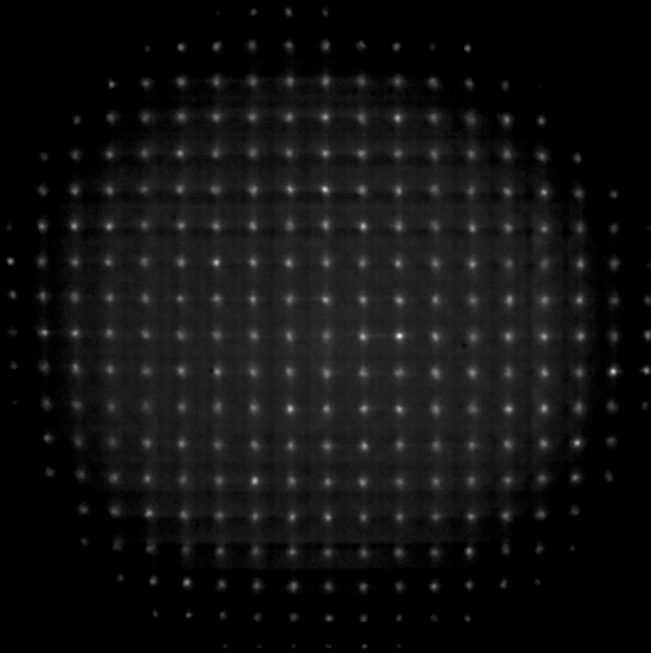
Diagnosis of High-order Aberrations

Shack-Hartmann Images

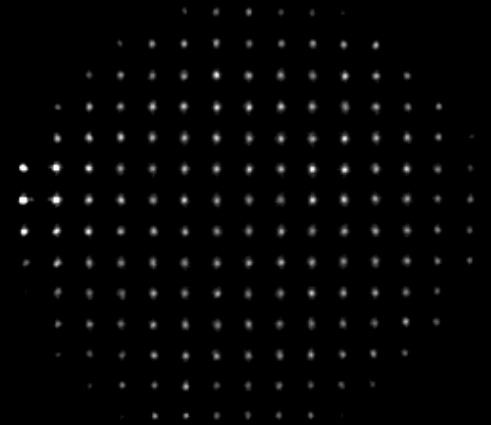
BD



KW



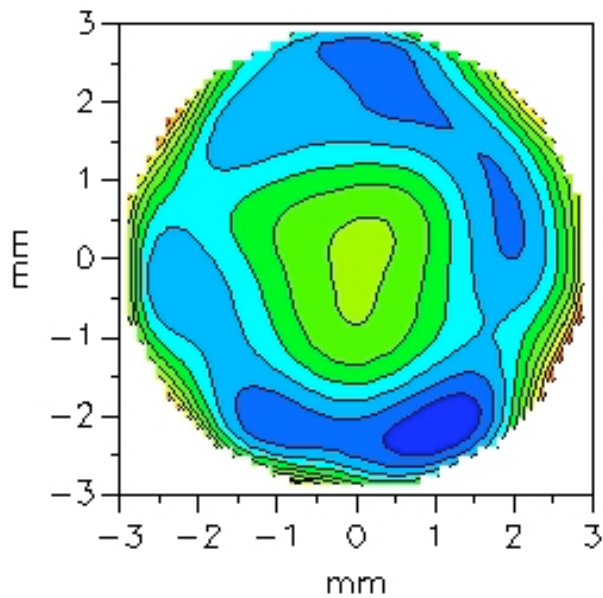
SM



Wavefront Maps

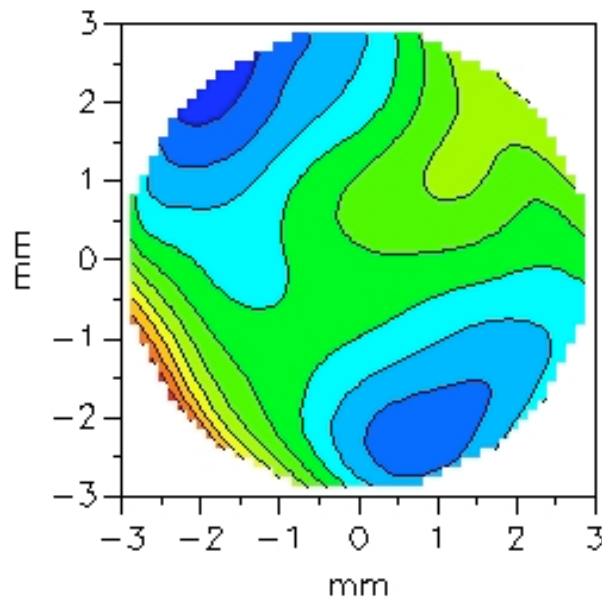
(at best focal plane)

BD



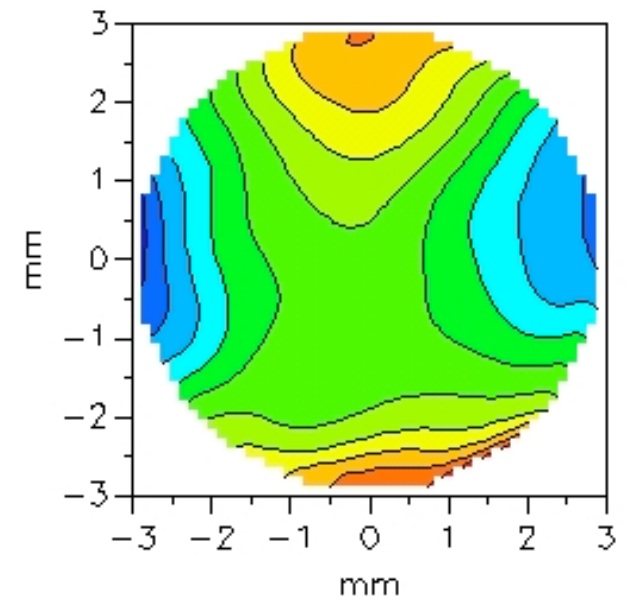
0.33 DS
-0.17 DC X 87

KW



6.42 DS
-0.6 DC X 126

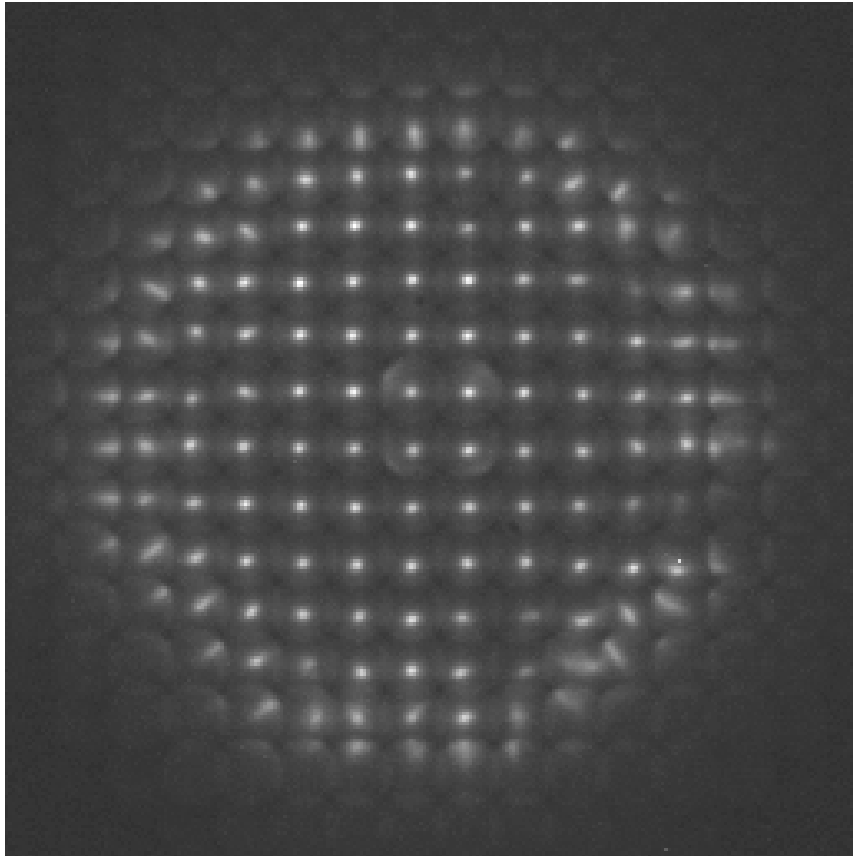
SM



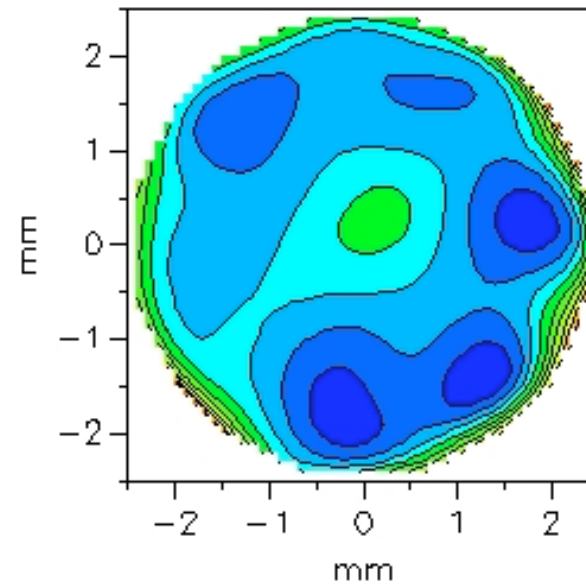
0 DS
-1 DC X 3

Aberrations of an RK patient

Wavefront sensor image

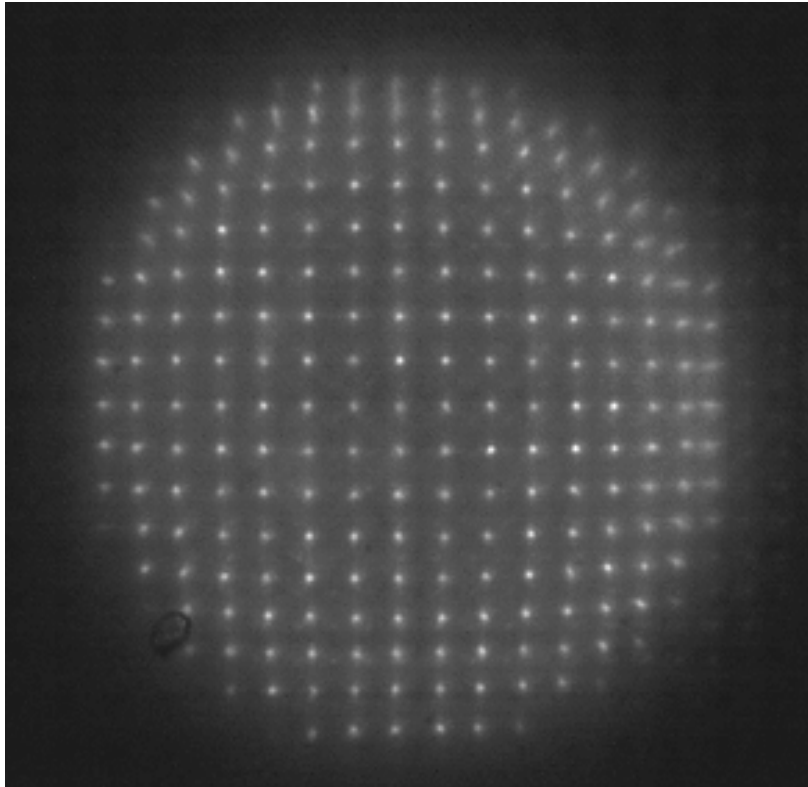


Wavefront aberration

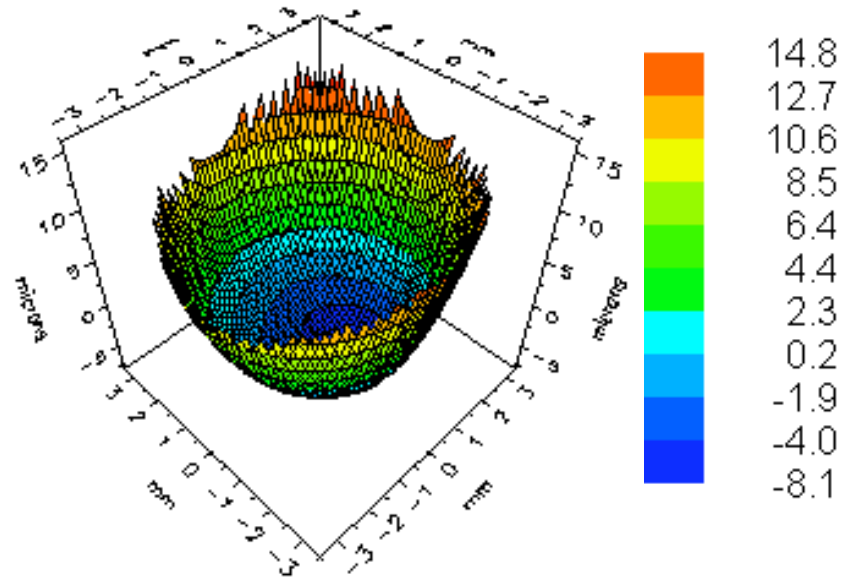


Aberrations of a LASIK patient

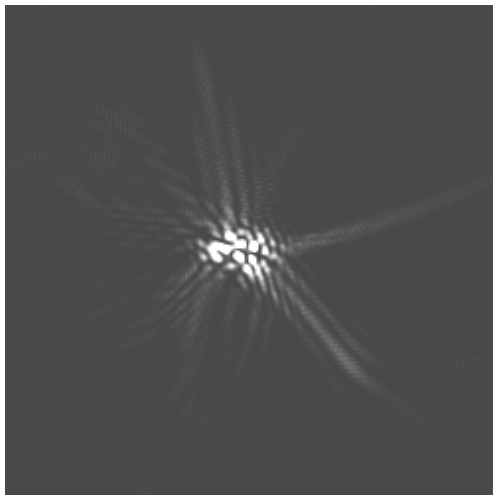
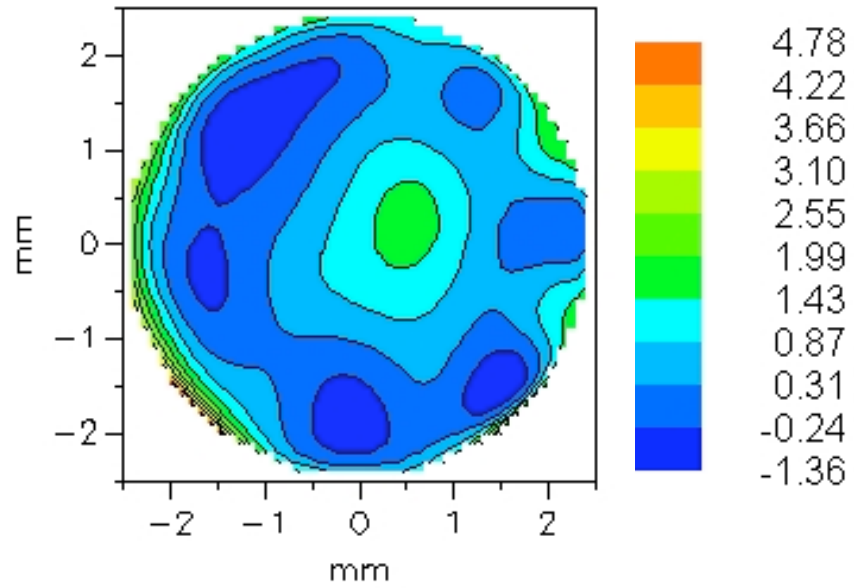
Wavefront sensor image



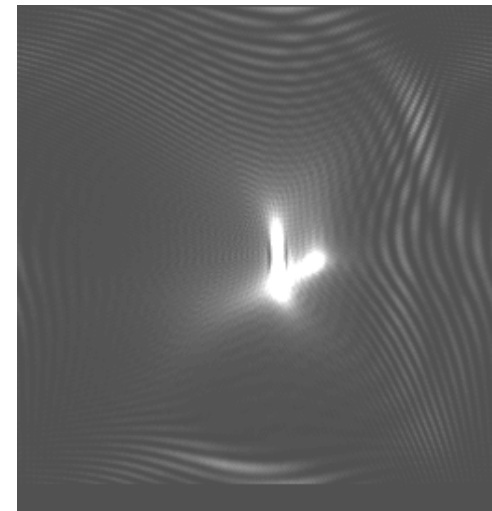
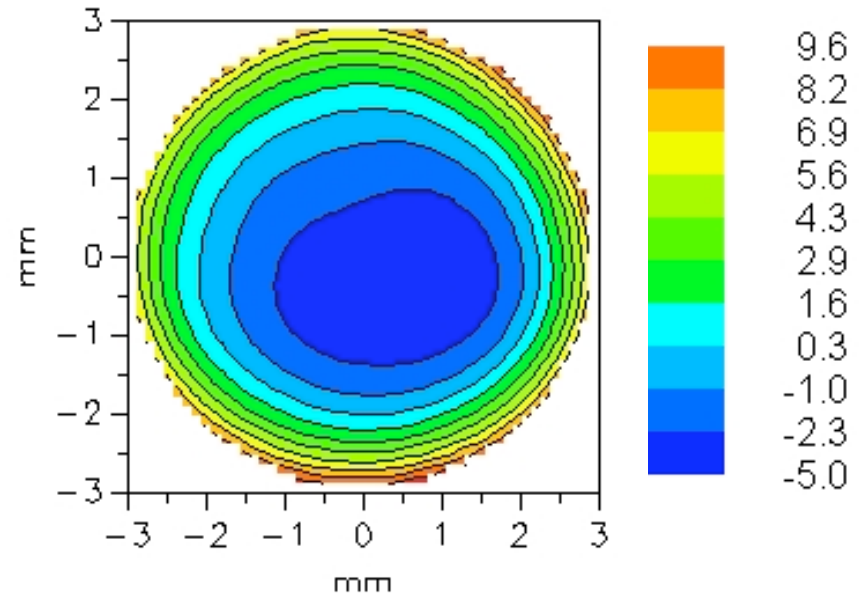
Wavefront aberration



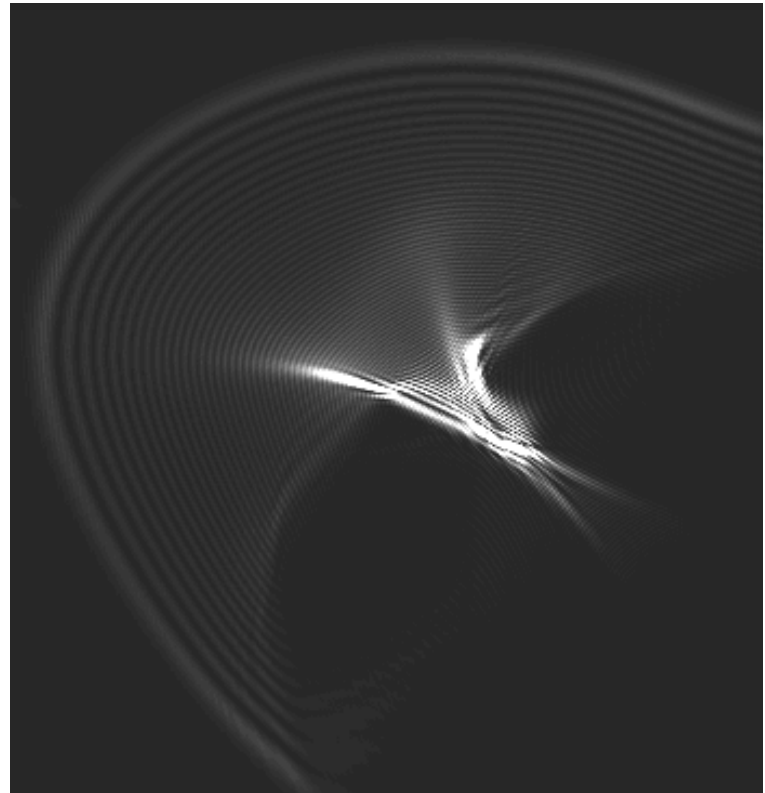
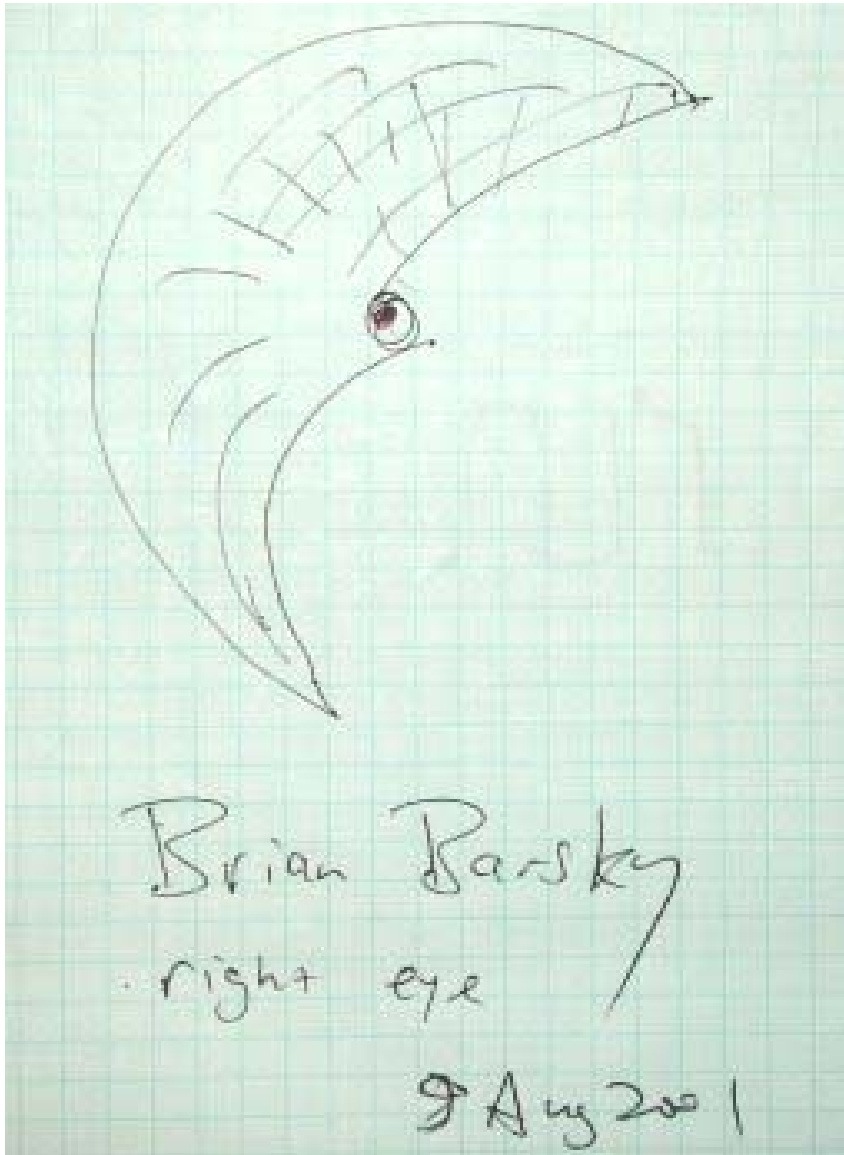
Post - RK



Post - LASIK

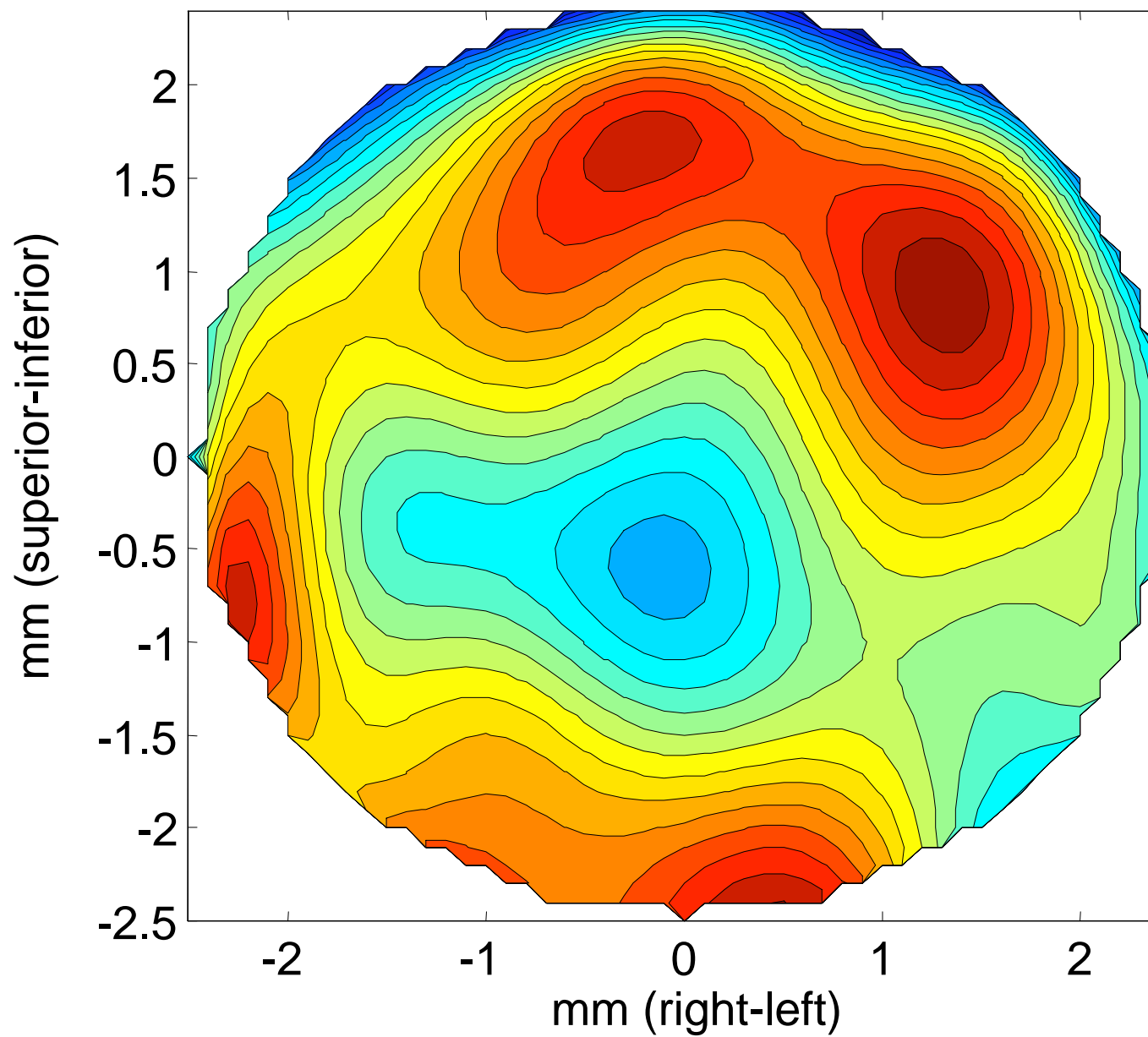


Keratoconus

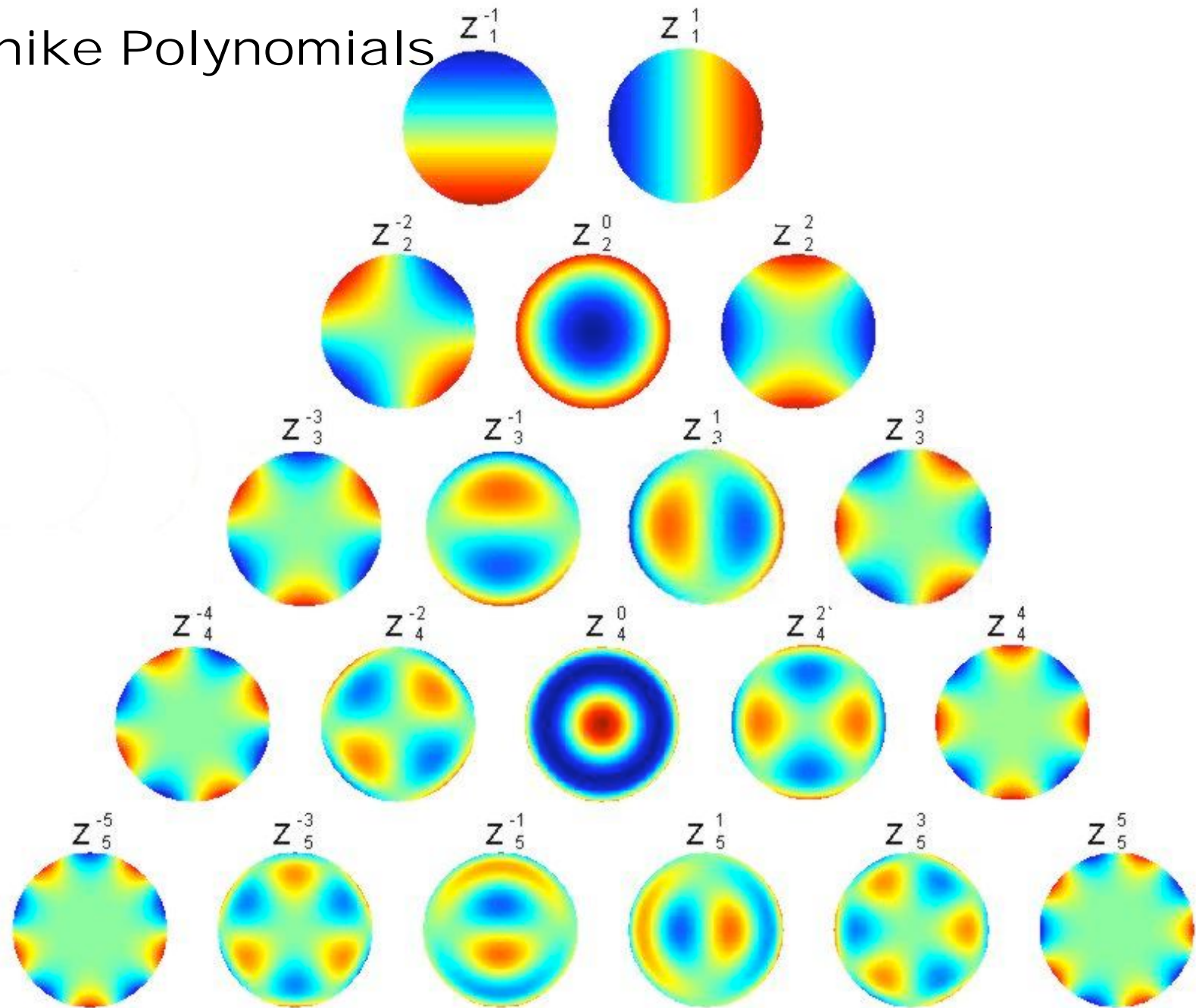


Metrics to Define Image Quality

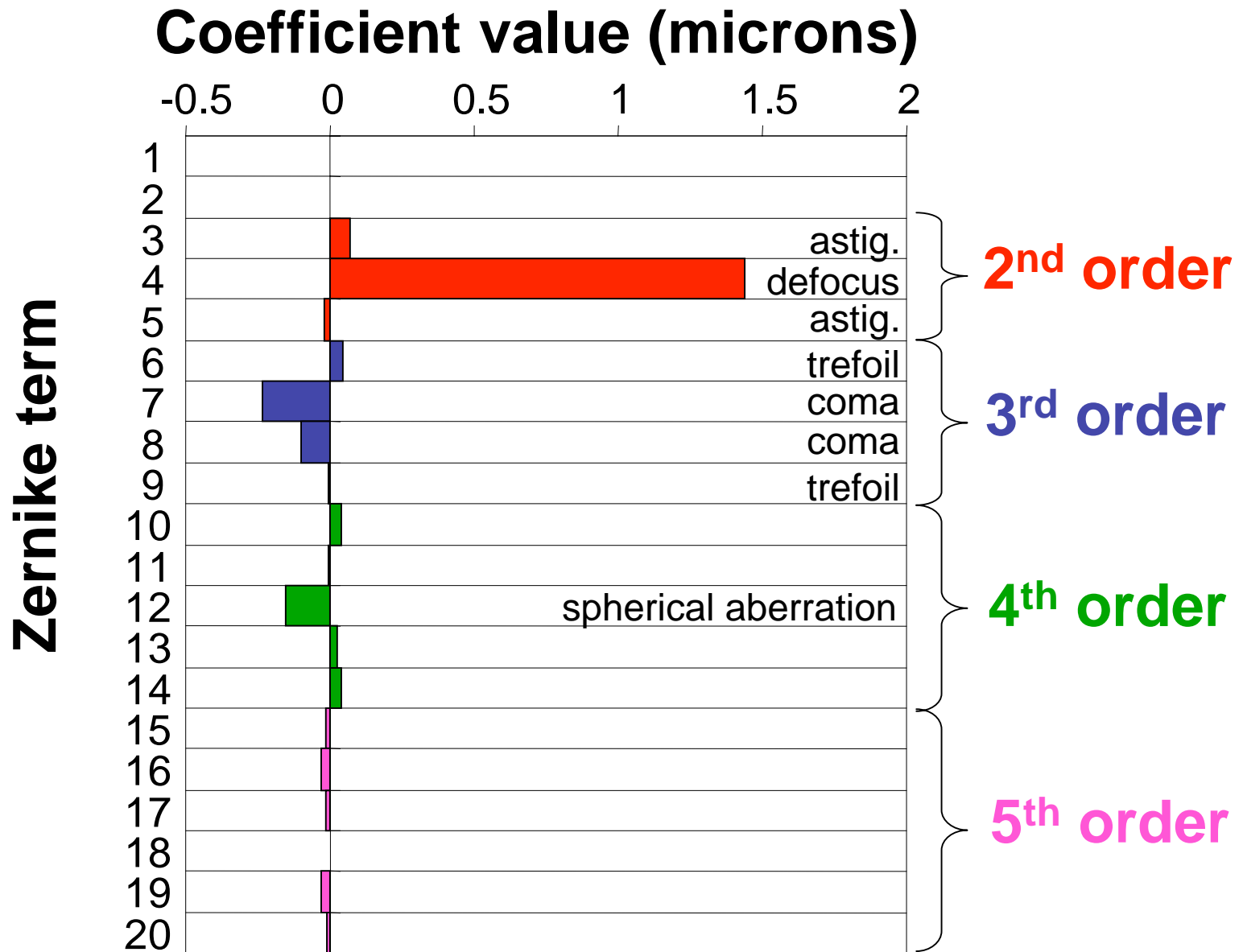
Wave Aberration Contour Map



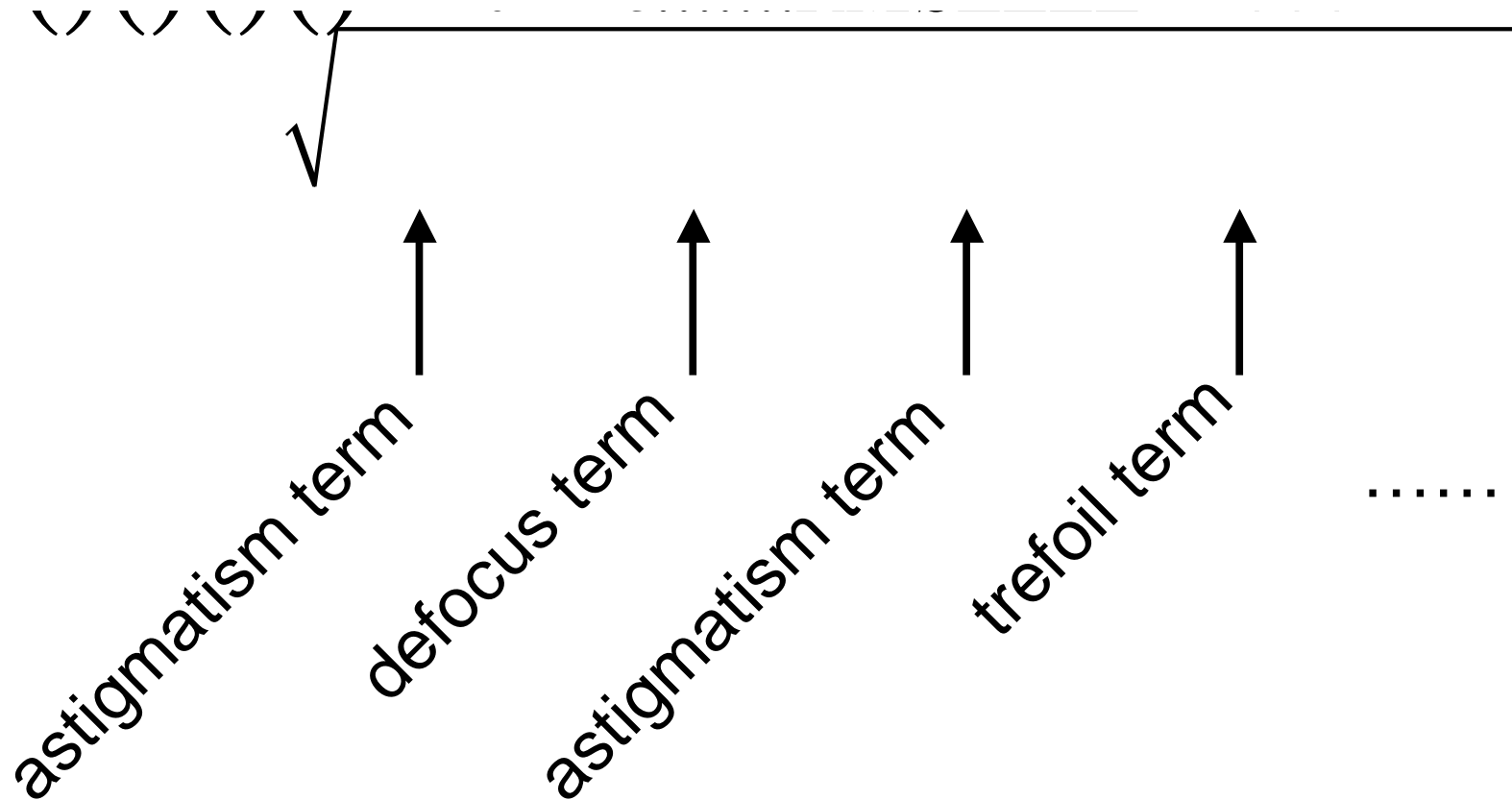
Zernike Polynomials



Breakdown of Zernike Terms

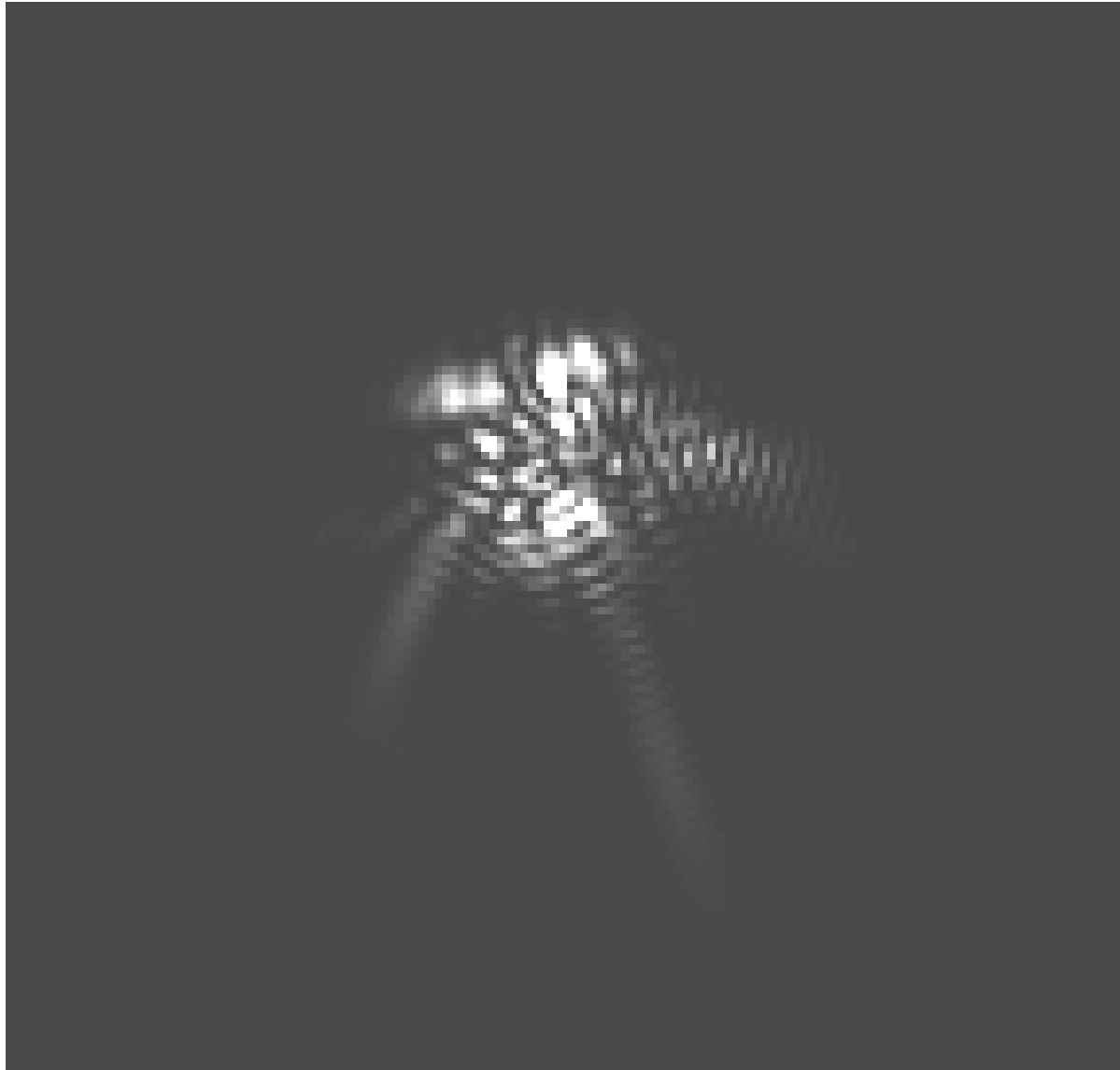


Root Mean Square



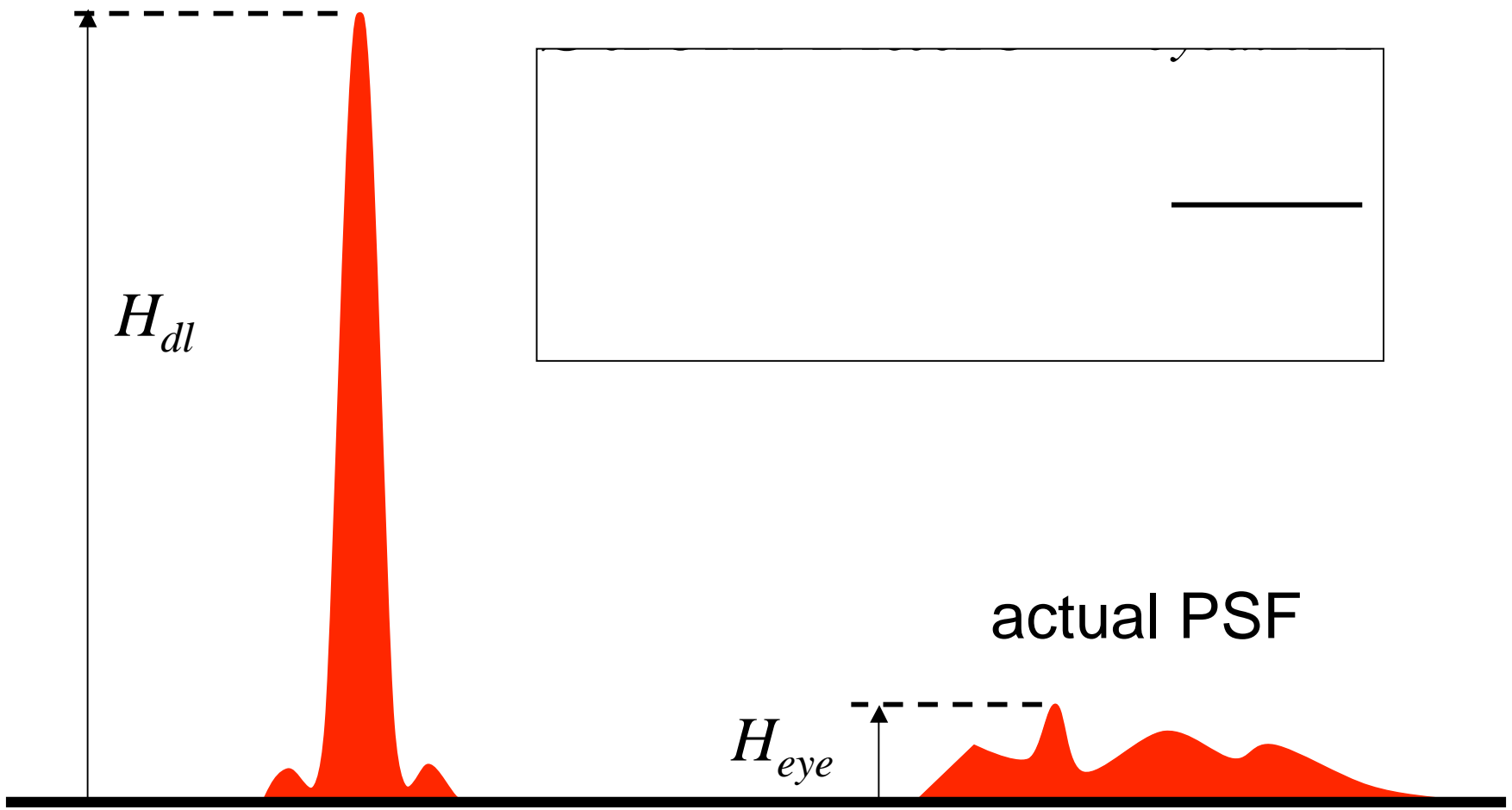
Include the terms for which you want to determine their impact (eg defocus and astigmatism only, third order terms or high order terms etc.)

Point Spread Function



Strehl Ratio

diffraction-limited PSF



Convolution

Convolution

\\ / \\ / \\ / - - - \\ / - - - \\ / - - -



Simulated Images

20/20 letters



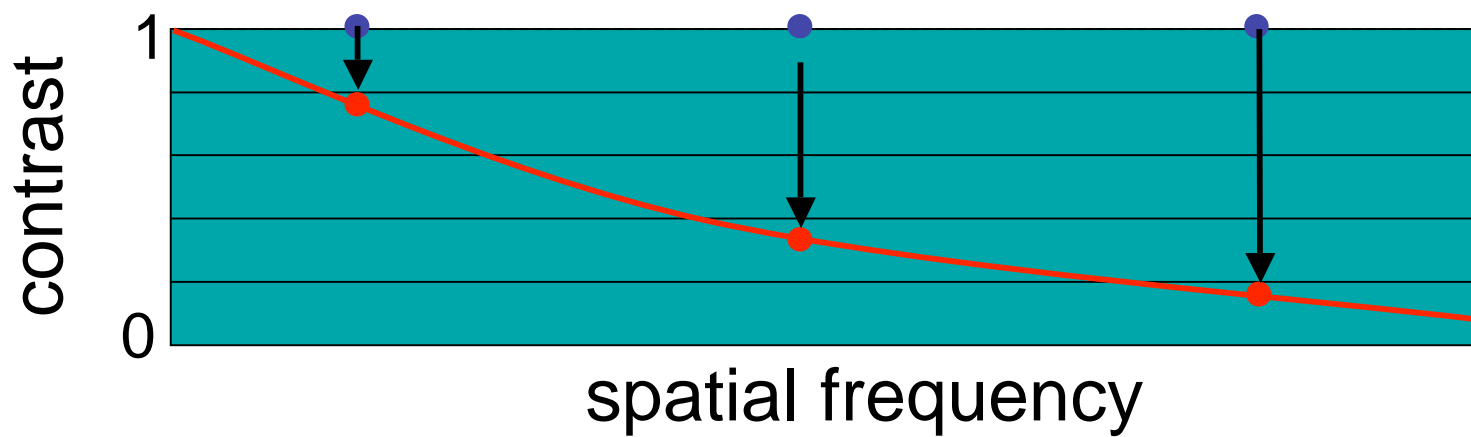
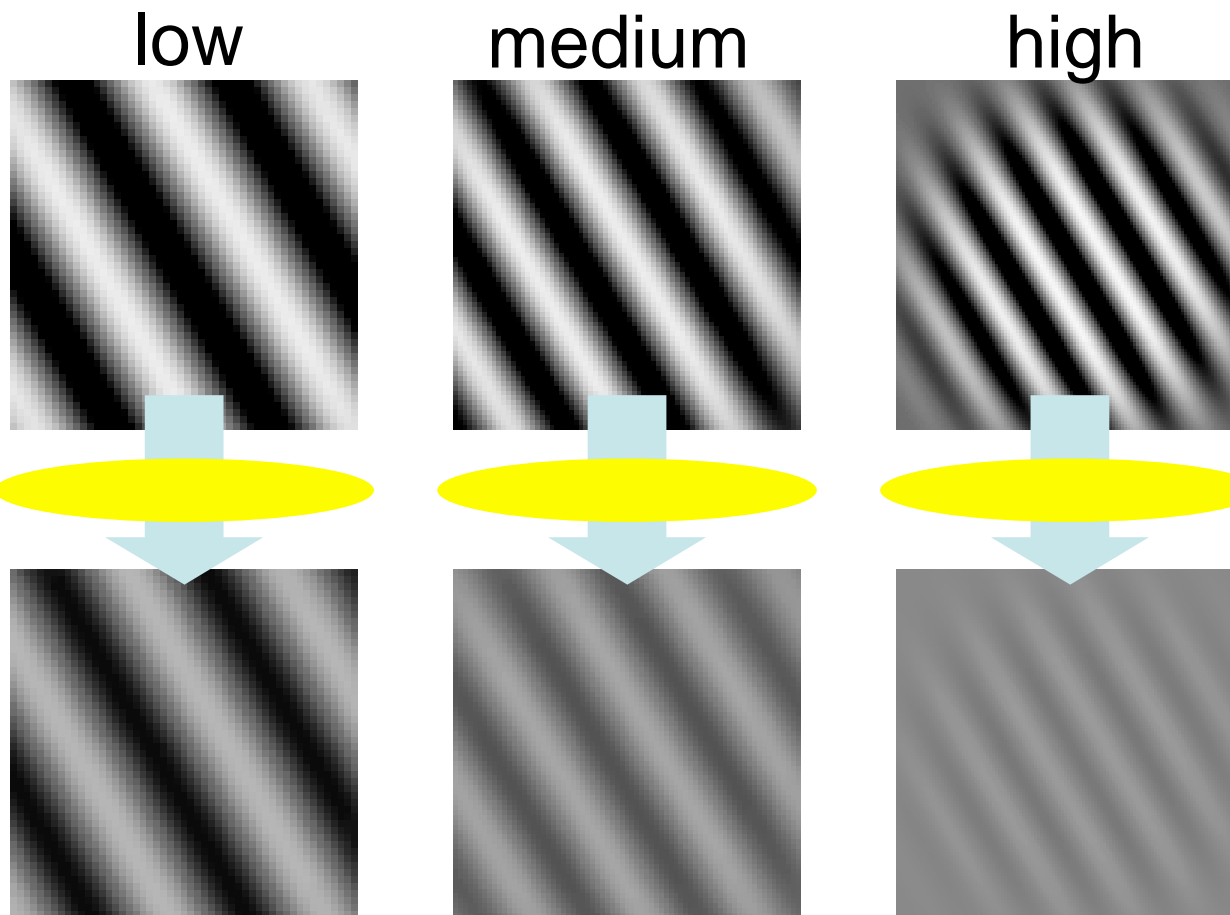
20/40 letters



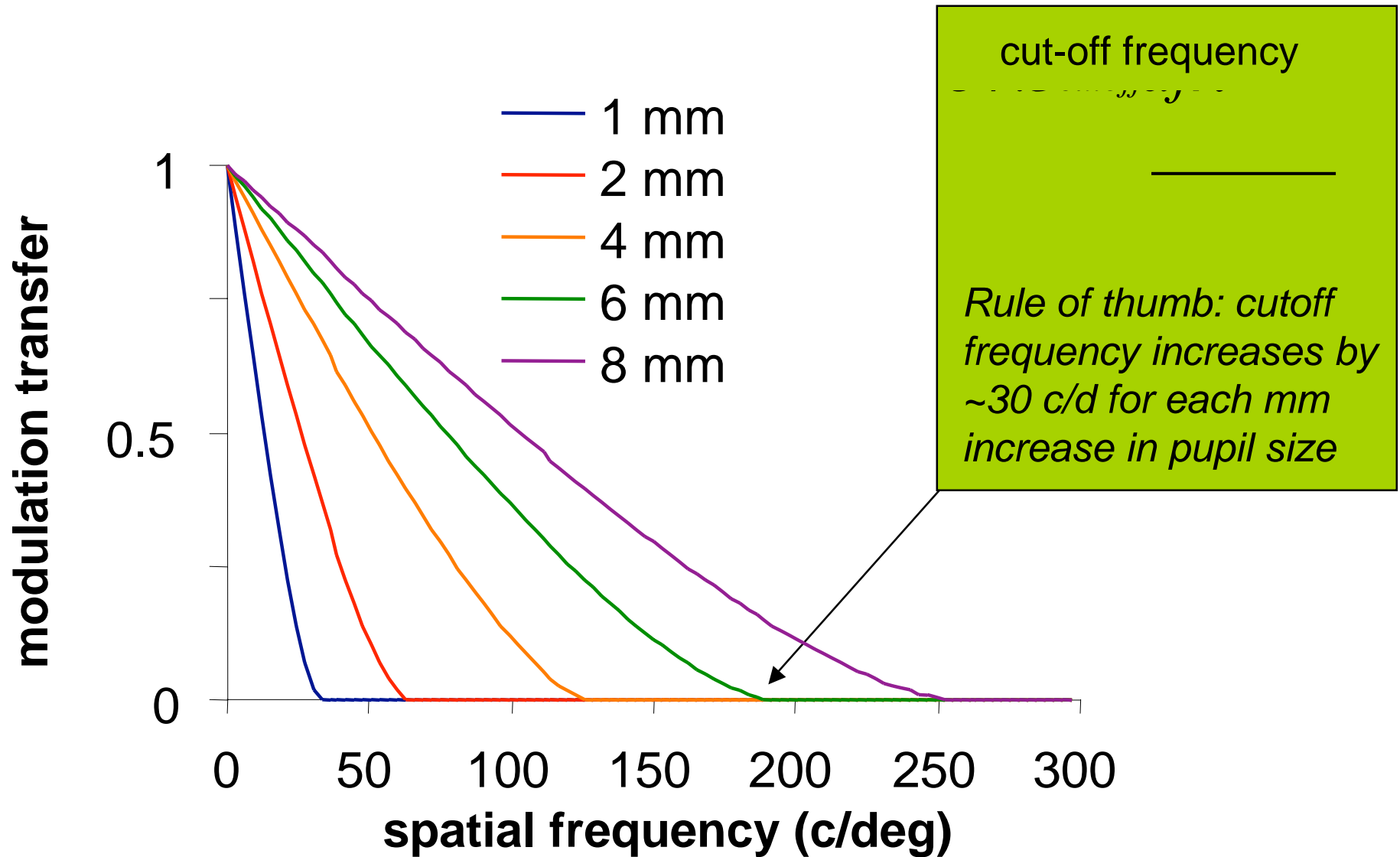
MTF

Modulation Transfer
Function

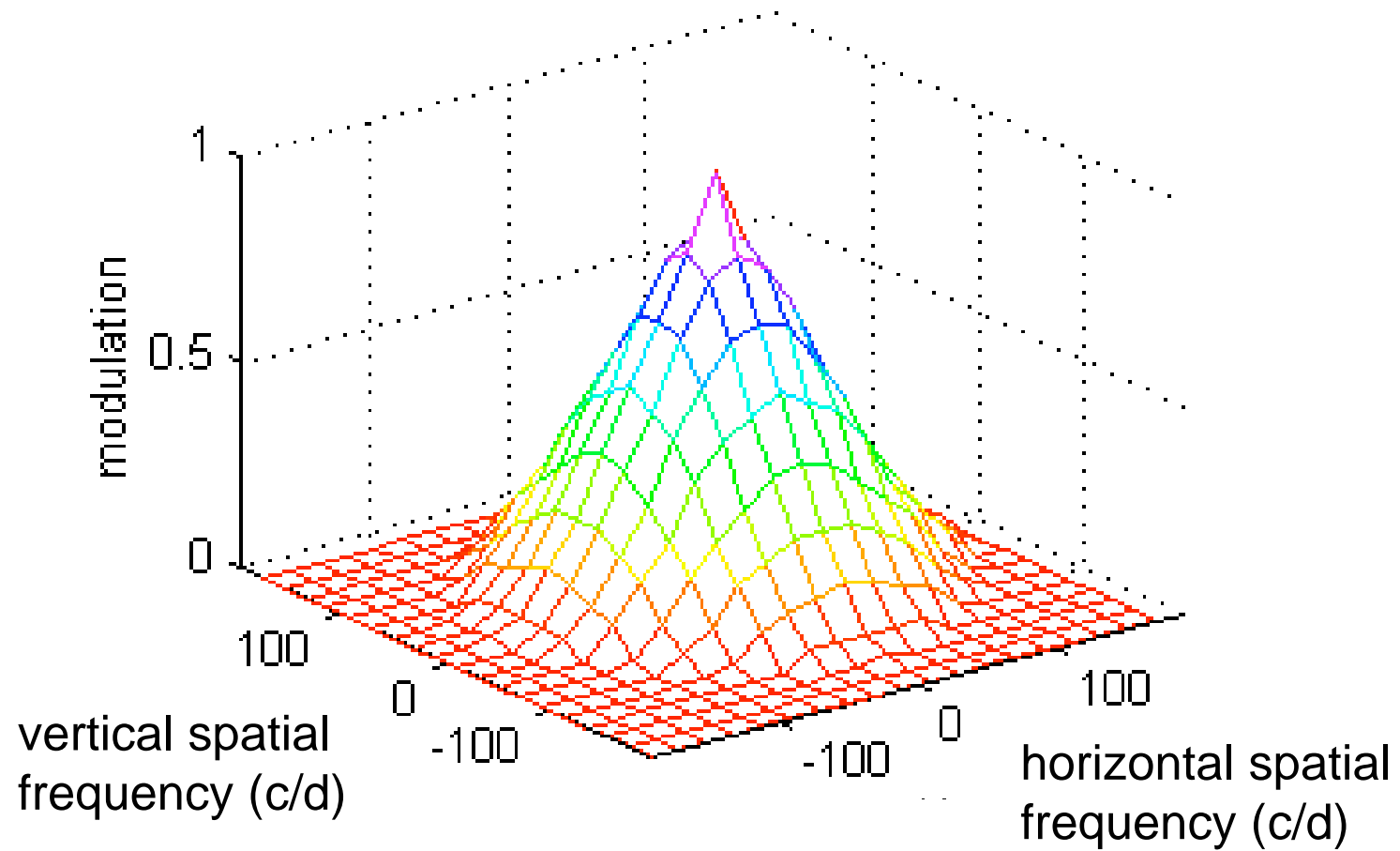
object:
100%
contrast



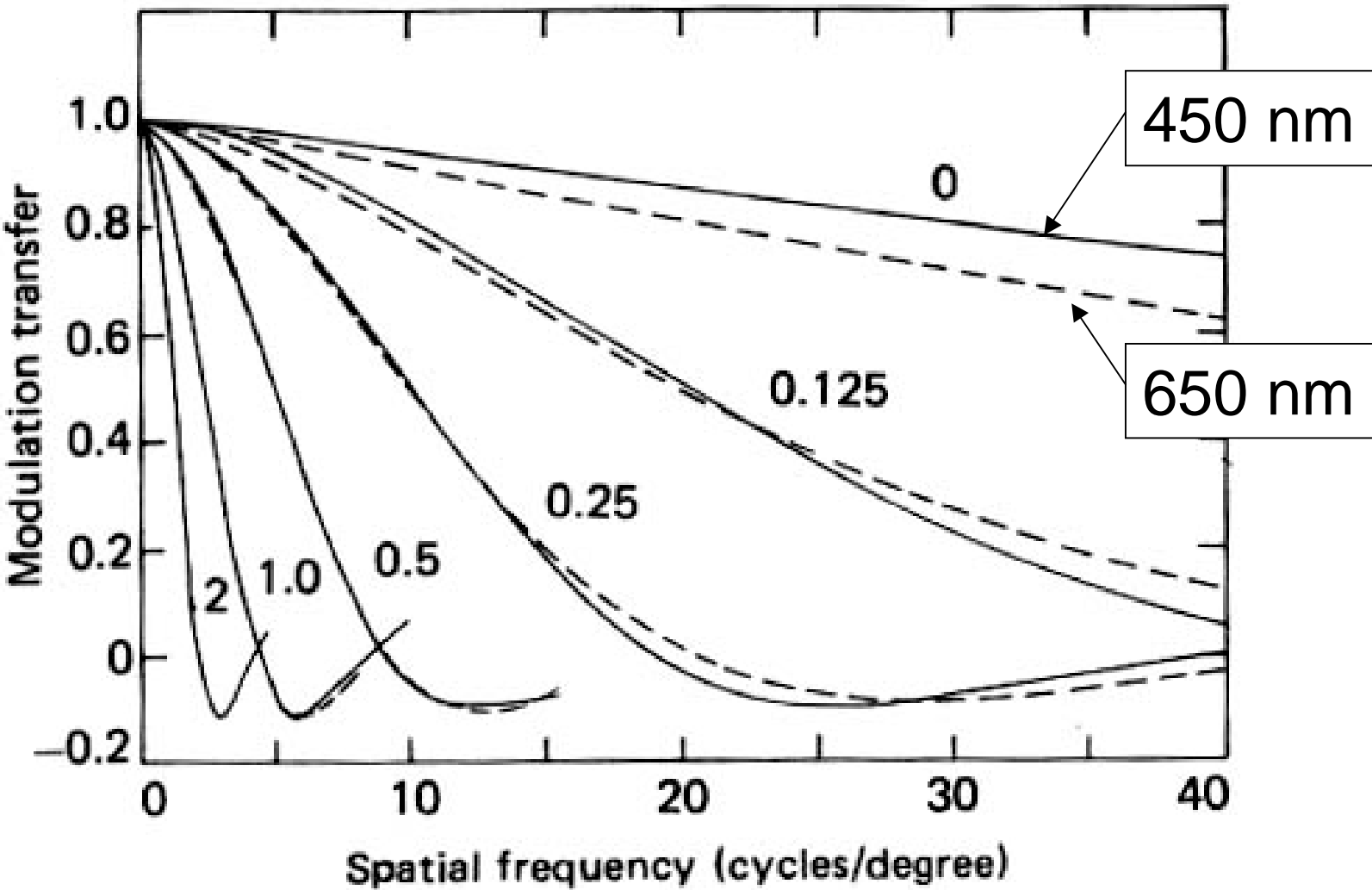
MTF: Cutoff Frequency



Modulation Transfer Function

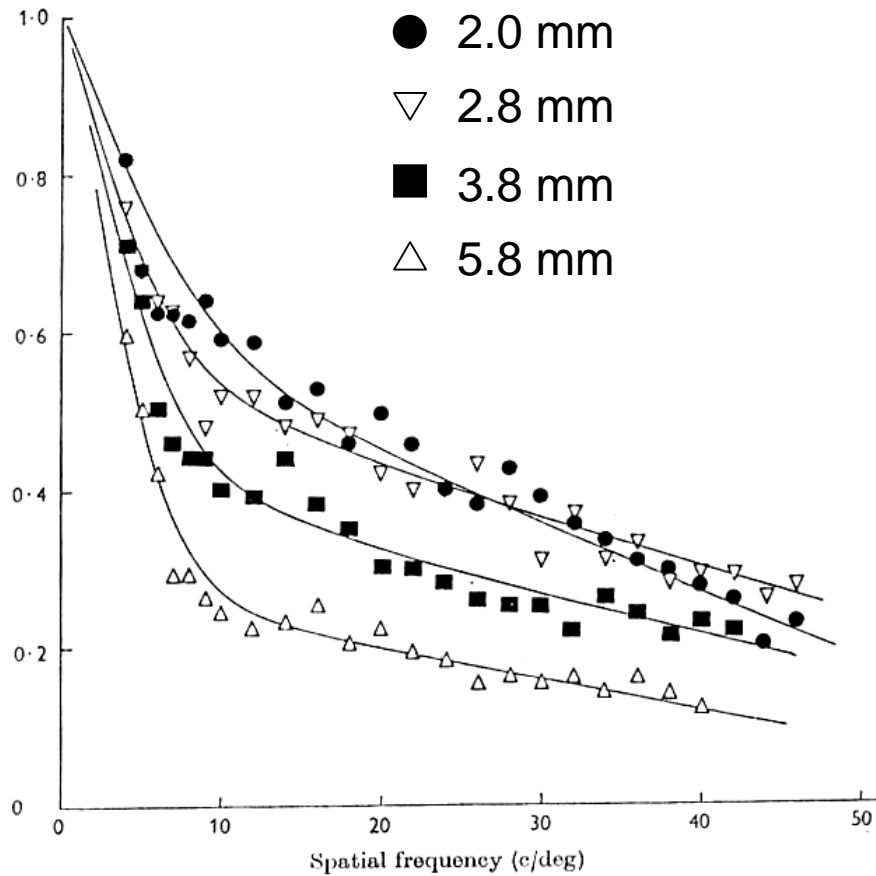


Effect of Defocus on the MTF

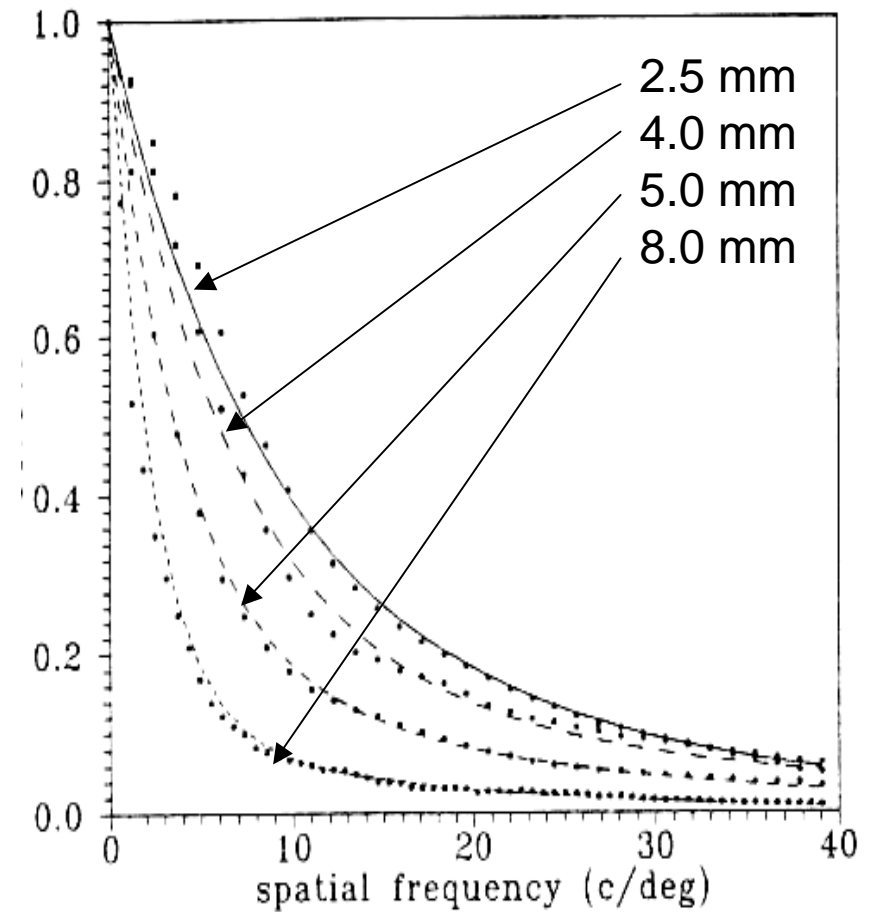


Charman and Jennings, 1976

Change in MTF with pupil size



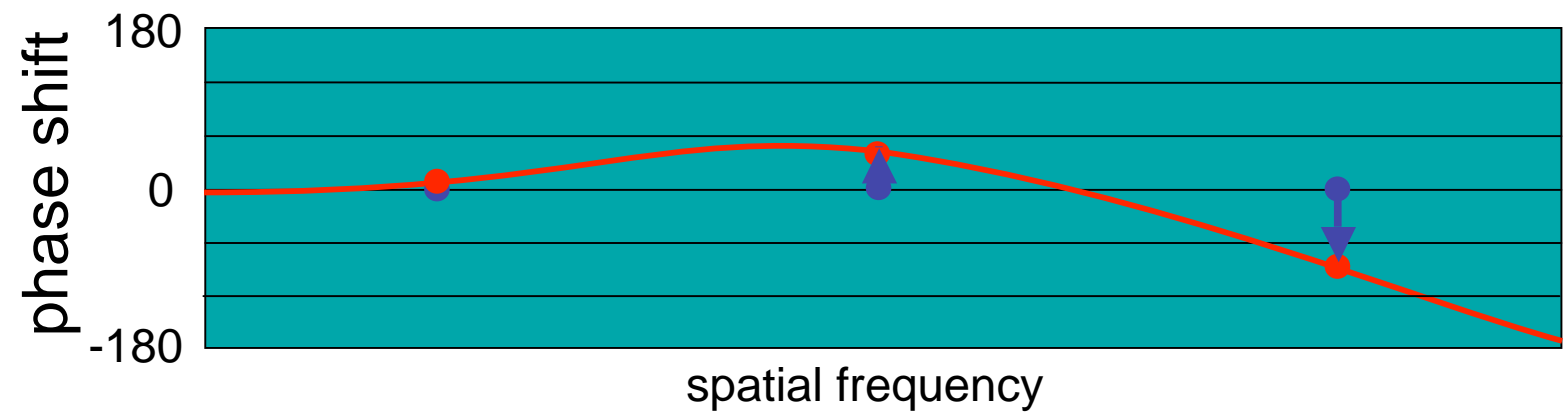
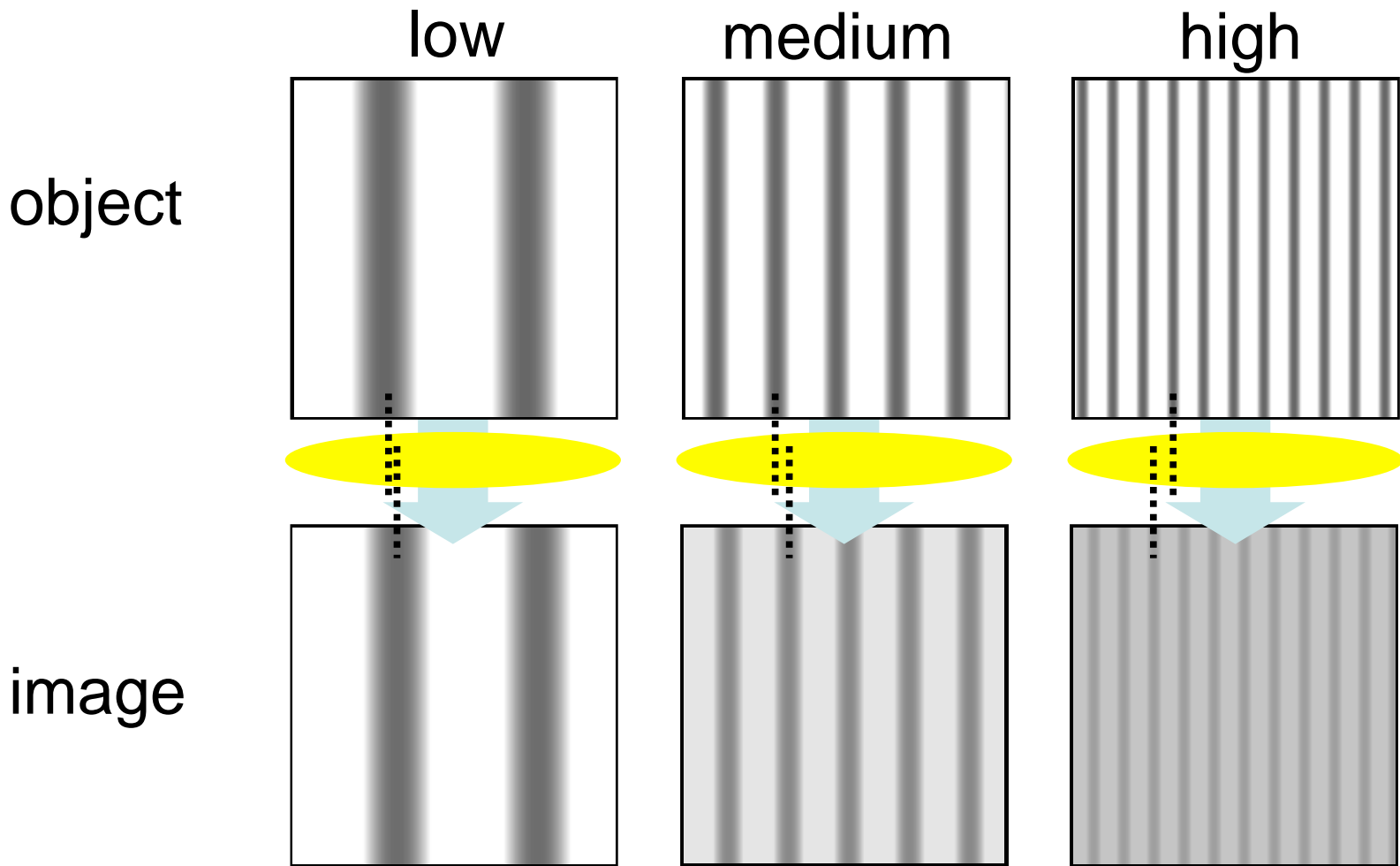
Campbell & Green 1965



Artal and Navarro 1994

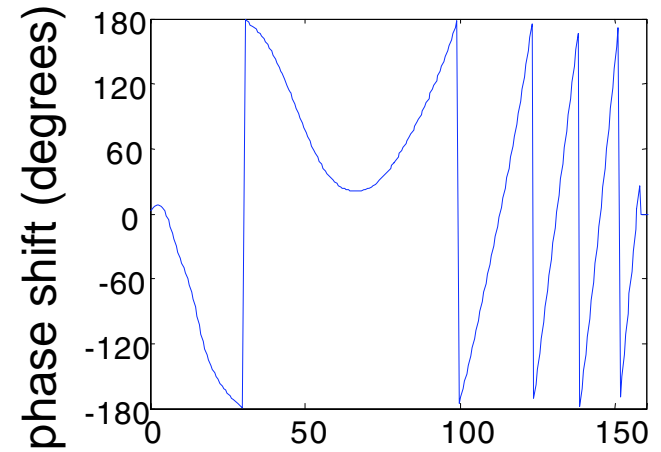
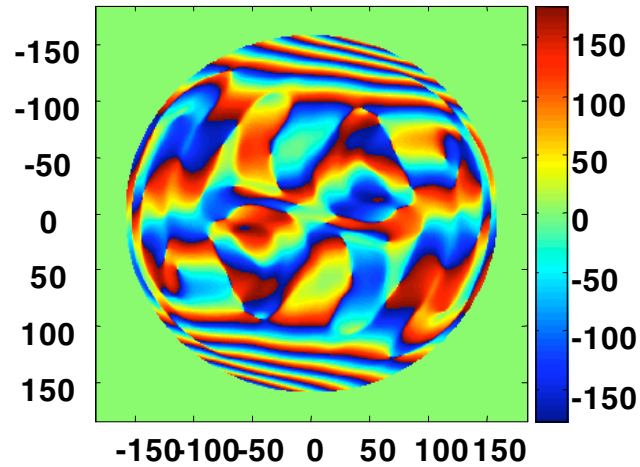
PTF

Phase Transfer
Function

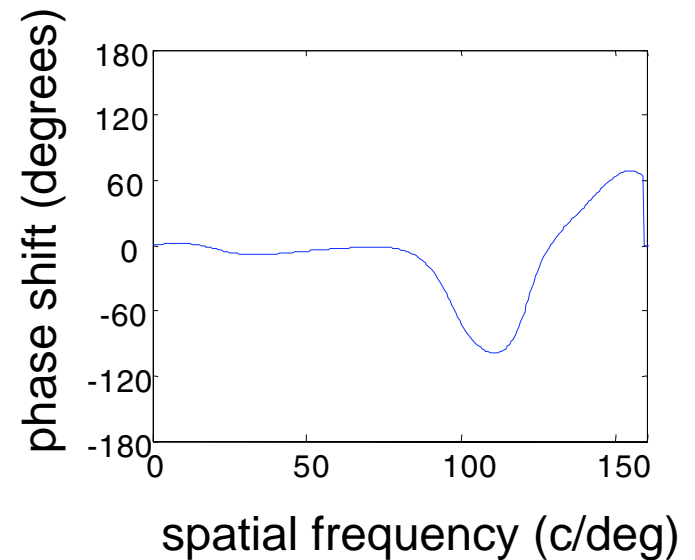
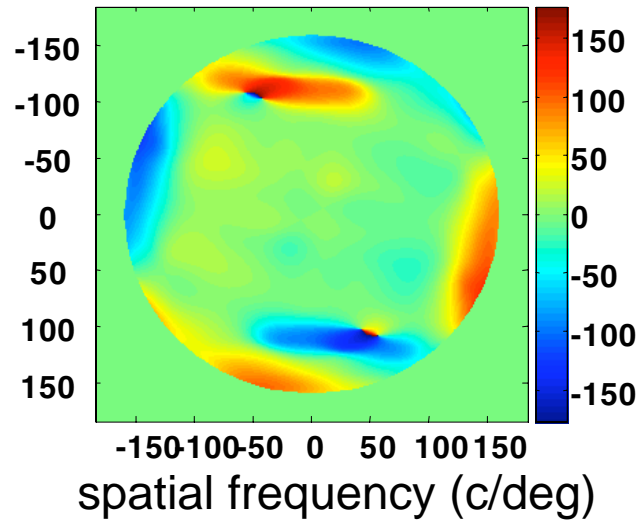


Phase Transfer Function

No AO
rms: $0.29 \mu\text{m}$



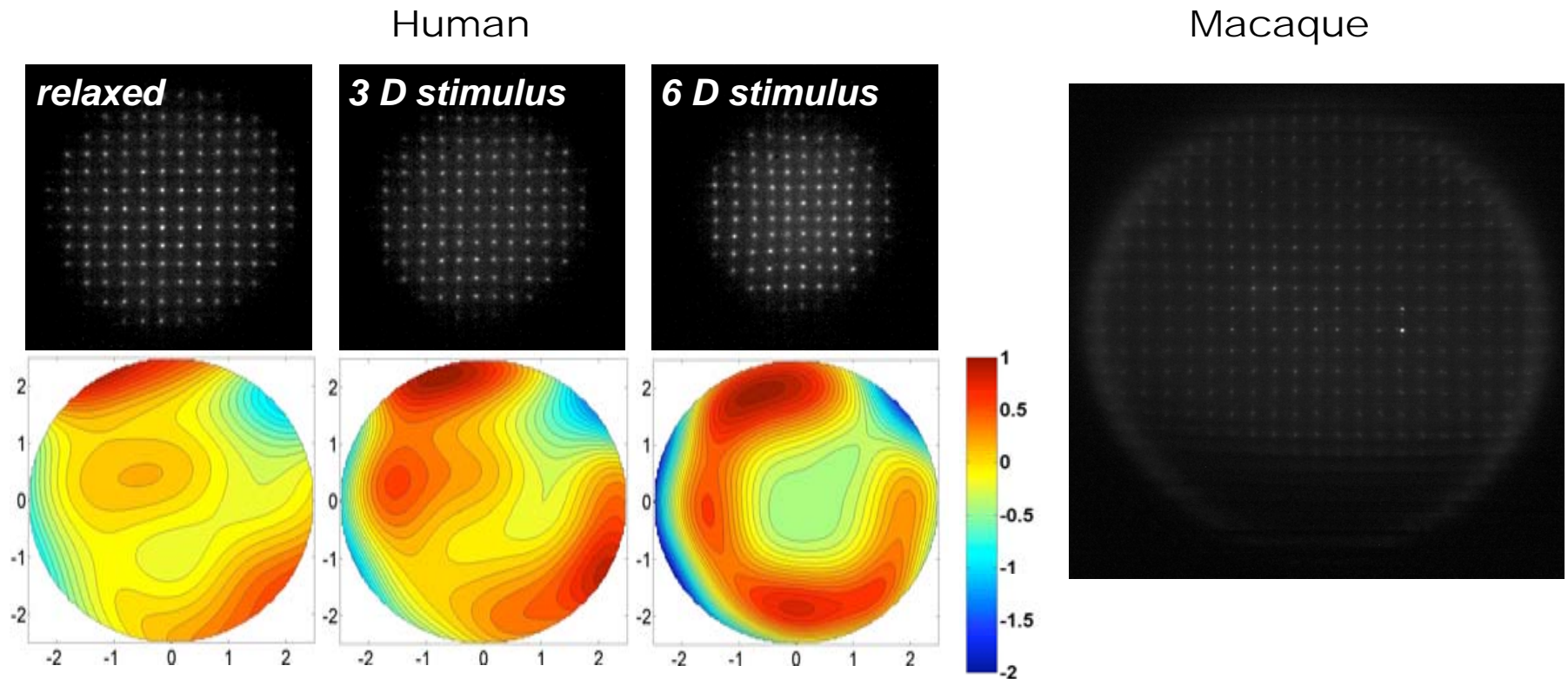
AO corrected
rms: $0.09 \mu\text{m}$



Why do we want to measure aberrations?

- Refractive surgery
- Presbyopia relief/correction
- Emmetropization and refractive development
- Accommodation

Aberrations Change with Accommodation

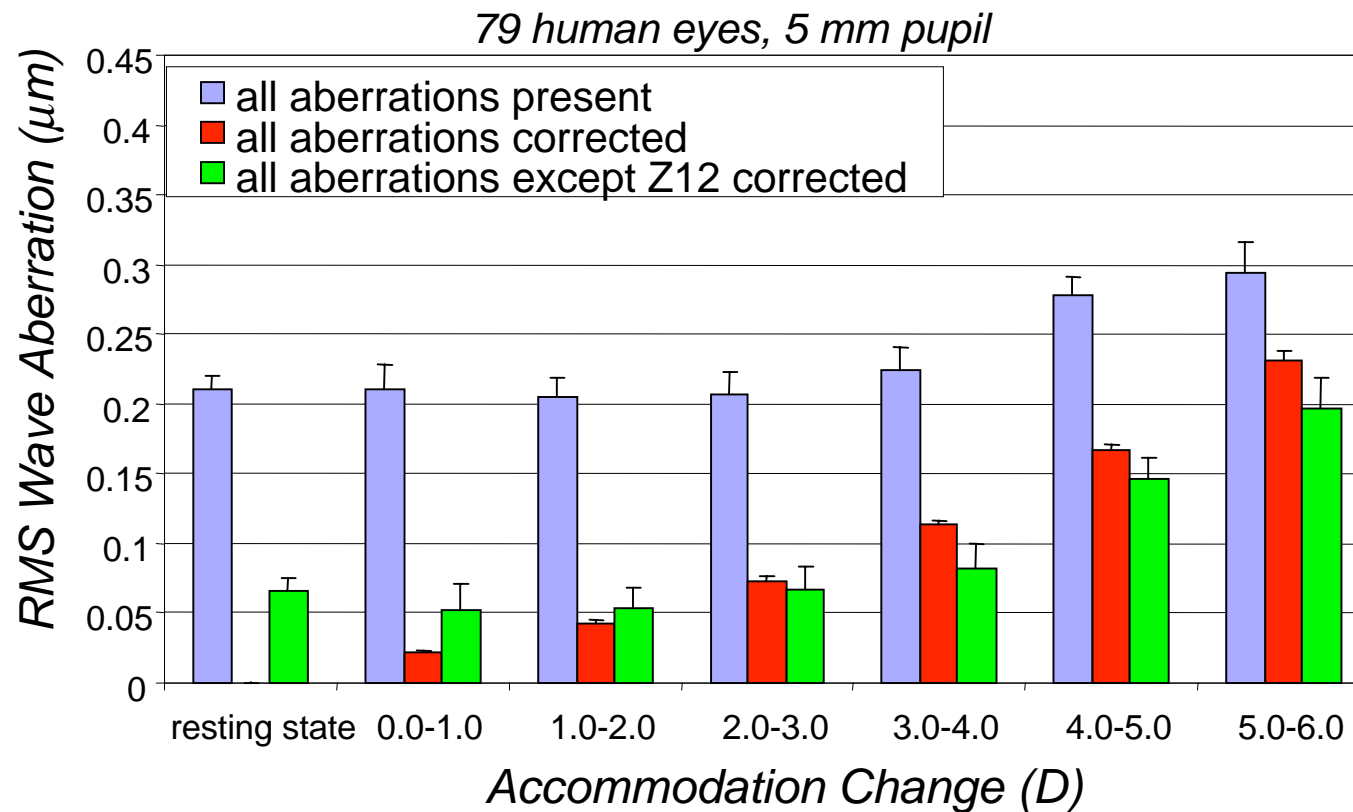


Cheng, H., Barnett, J.K., Vilupuru, A.S., Marsack, J.D., Kasthurirangan, S., Applegate, R.A., **Roorda, A.** "A Population Study on Changes in Wave Aberration with Accommodation" **submitted to** Journal of Vision. (2003)

Vilupuru, A., **Roorda, A.**, Glasser, A. "Spatially Variant Changes in Lens Power During Ocular Accommodation in a Rhesus Monkey Eye" **submitted to** Journal of Vision (2003)

Refractive Surgery

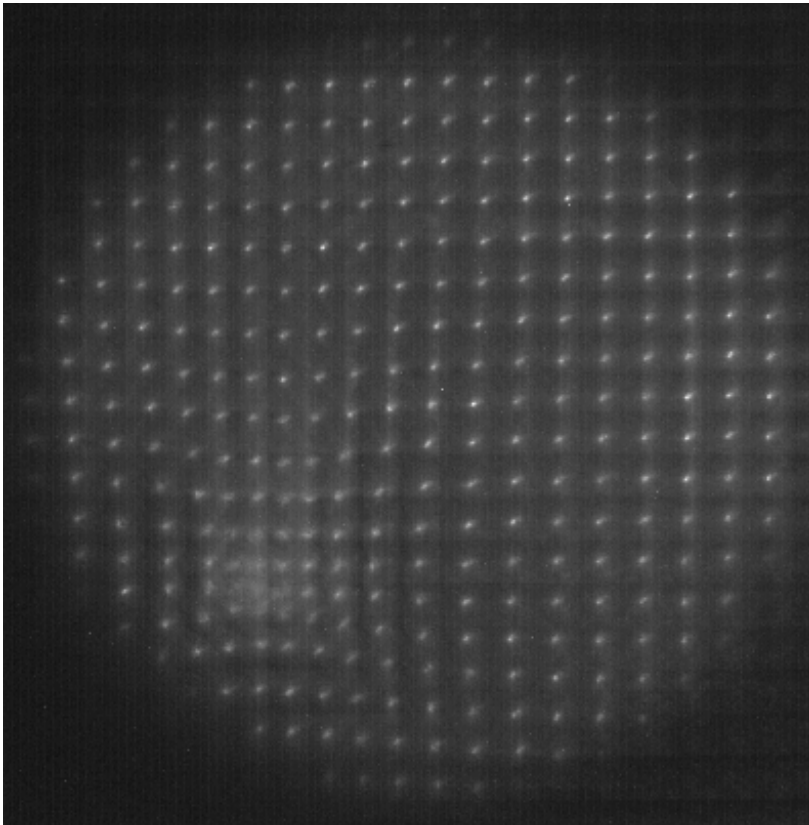
- Do aberration changes with accommodation preclude a good aberration-free correction?



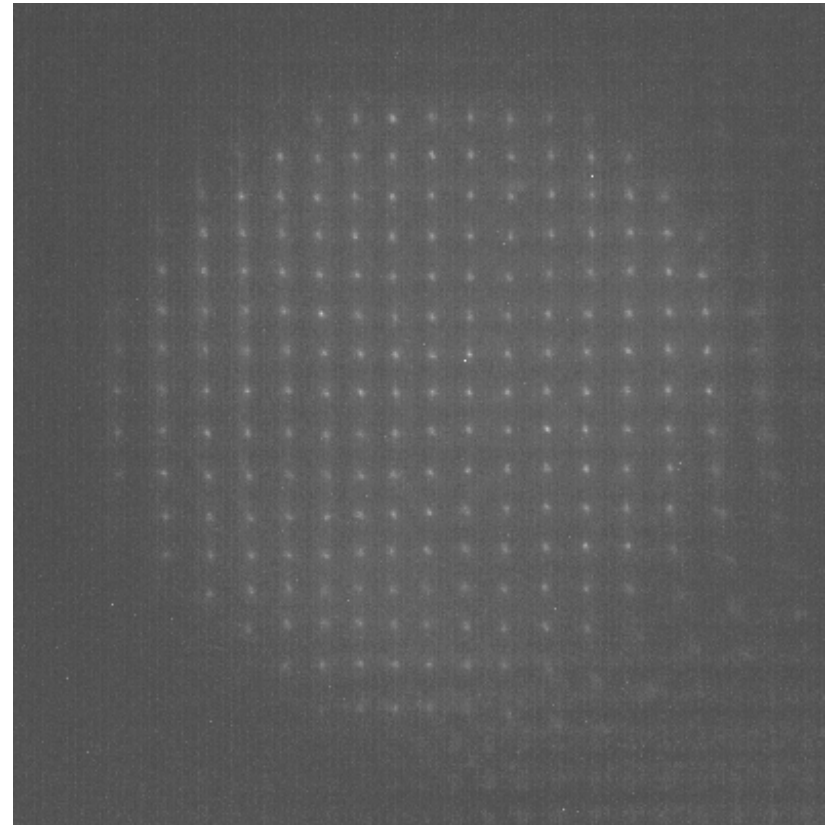
Cheng, H., Barnett, J.K., Vilupuru, A.S., Marsack, J.D., Kasthurirangan, S., Applegate, R.A., **Roorda, A.** "A Population Study on Changes in Wave Aberration with Accommodation" **submitted to** Journal of Vision. (2003)

Contact Lenses for Keratoconus

unaided eye

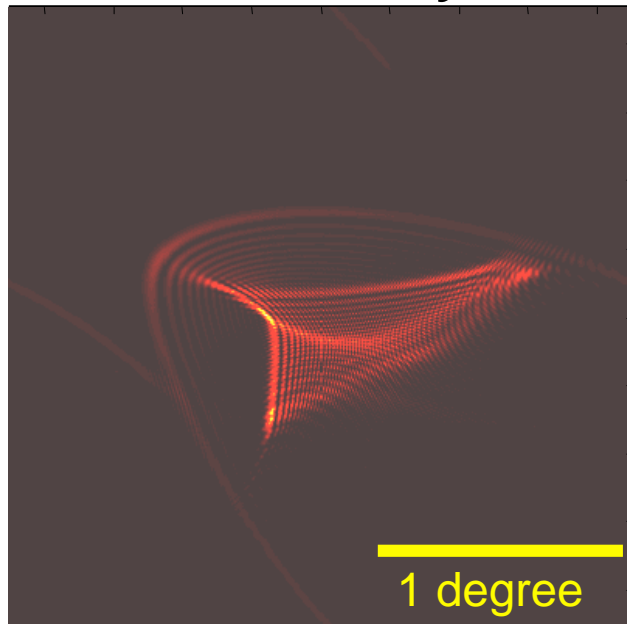


custom contact lens



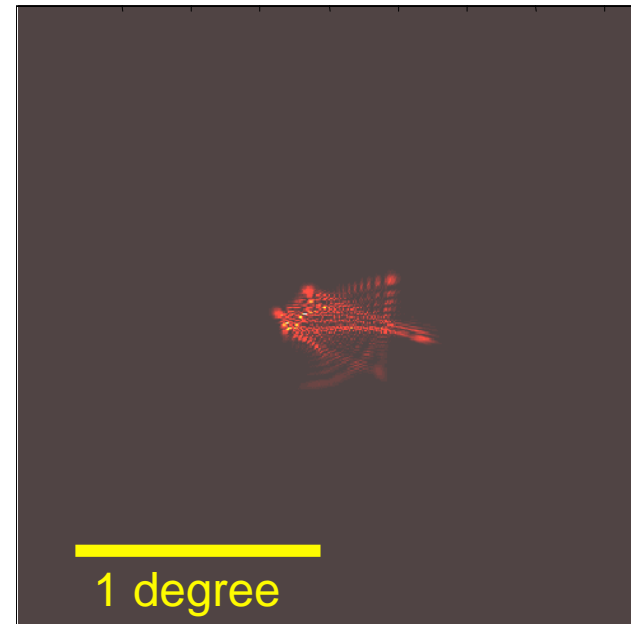
PSFs (for 5 mm pupil)

unaided eye



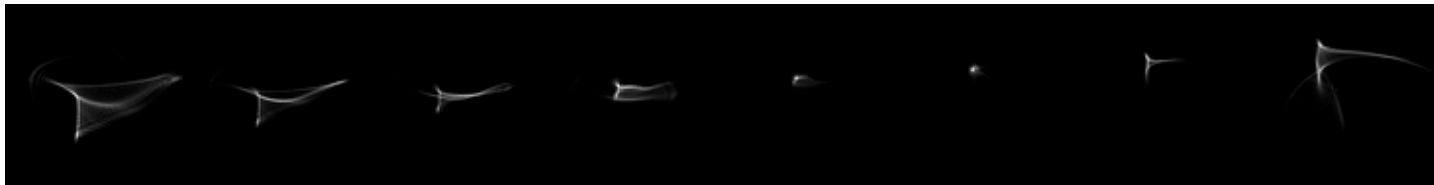
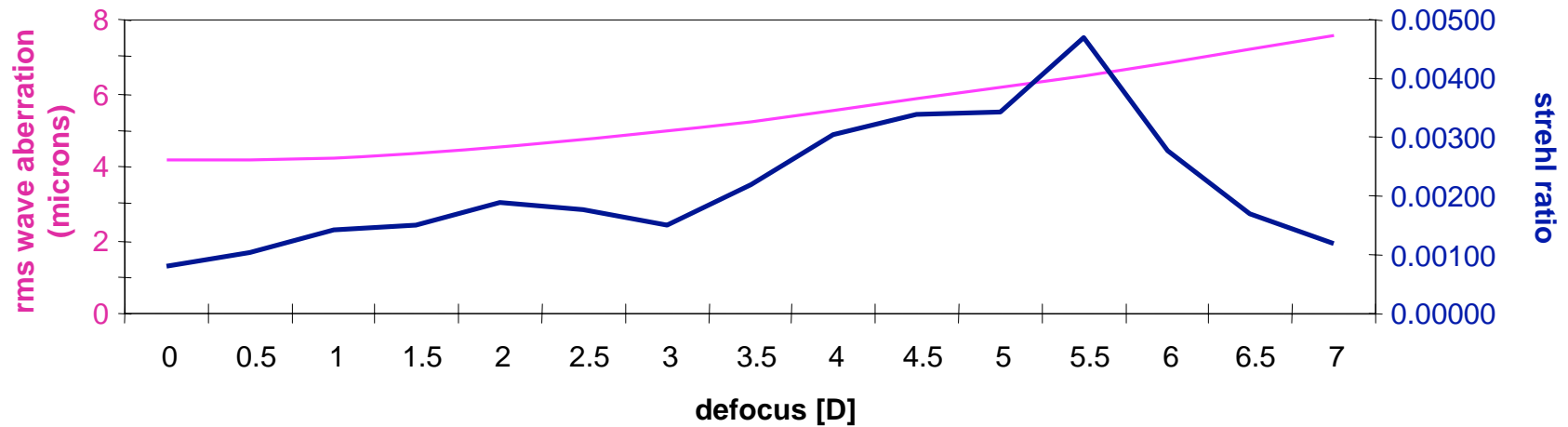
rms = 4.16
strehl ratio = 0.0008

custom contact lens



rms = 1.48
strehl ratio = 0.004

PSF through-focus (5 mm pupil)



The highest strehl ratio does not correlate with rms when aberrations are high

Presbyopia Relief

- Is a good multifocal or bifocal contact lens correction precluded by the presence of aberrations?

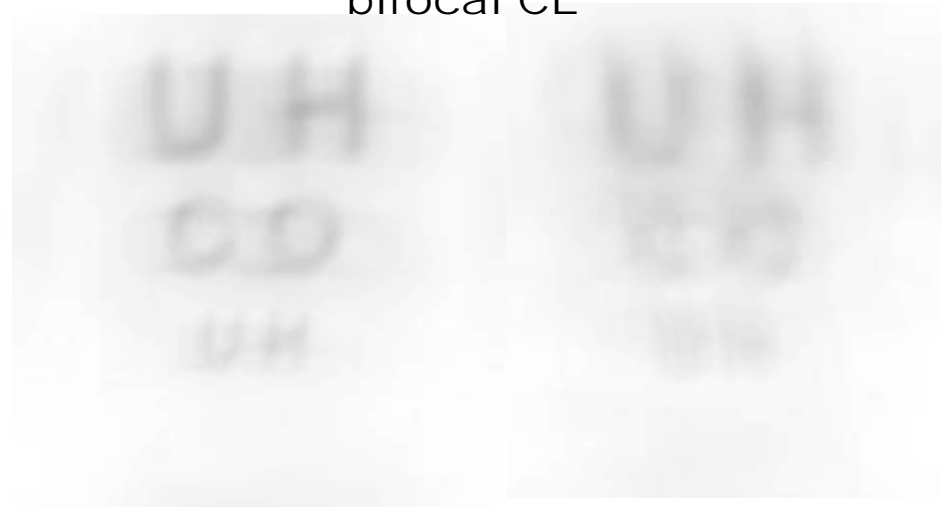
model eye
no CL



model eye
bifocal CL



two different human eyes
bifocal CL

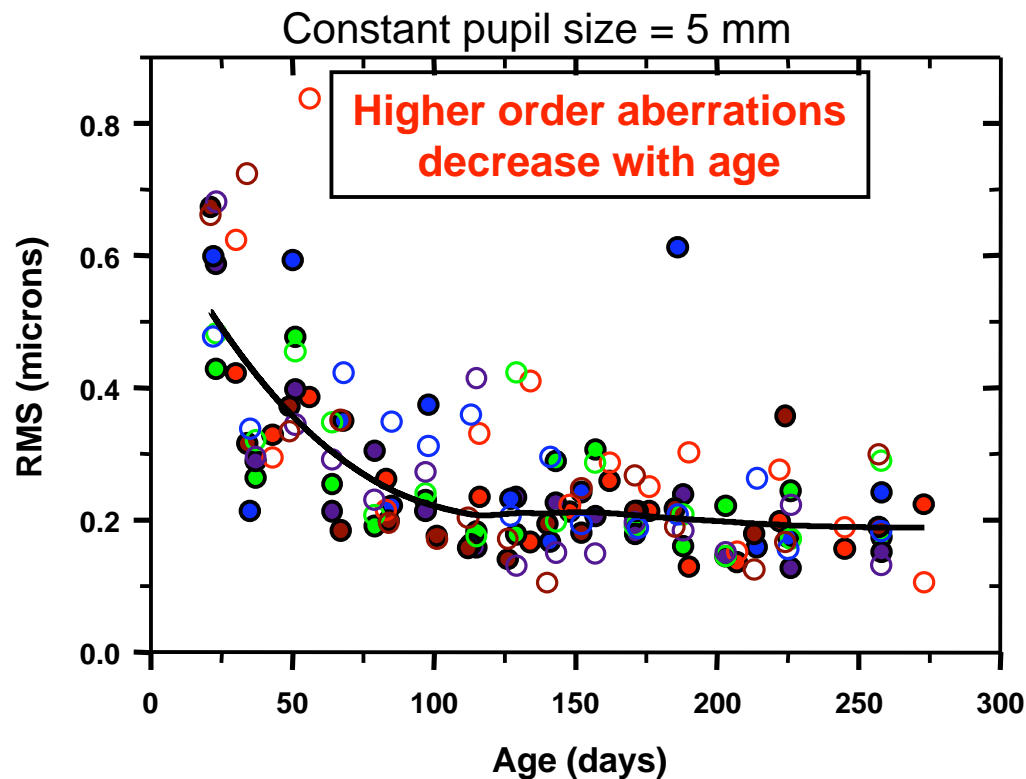


“Bifocal lenses do not always provide bifocal vision”

Martin, J.A., **Roorda, A.** “Predicting and Assessing Visual Performance with Multizone Contact Lenses” *Optom. Vision Sci.* 80(12): 812-819 (2003)

Emmetropization

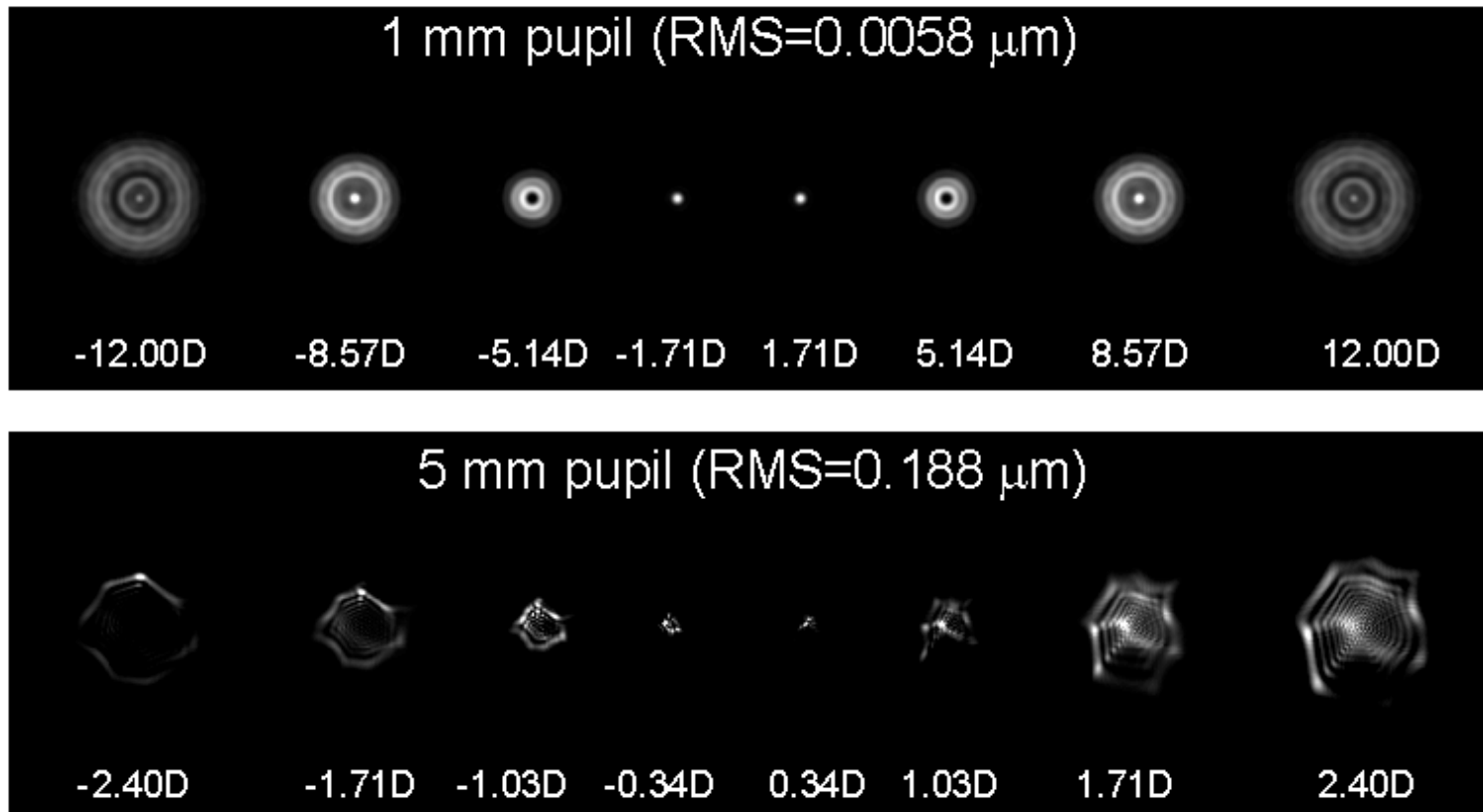
- Does the emmetropization process extend to aberrations beyond defocus?



Ramkumar Ramamirtham, Earl Smith, Austin Roorda

Accommodation

- Can aberrations provide a cue to indicate the sign of defocus for accommodation?



Wilson, B.J., Decker, K.E., **Roorda, A.** "Monochromatic Aberrations Provide an Odd-Error Cue to Focus Direction" J. Opt. Soc. Am. A. 19(5) 833-839 (2002).

Why Understand the Limits?

- People with normal vision do not complain about image quality, but presbyopes complain all the time
- There is an enormous image quality reserve in the eye
- Improved optics can be used to provide both improved vision AND increased depth of focus