NUI Galway
OÉ Gaillimh

An Grúpa Optaice Feidhmí
applied optics
PHYSICS

Simple Physics for Better Vision

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Erlangen
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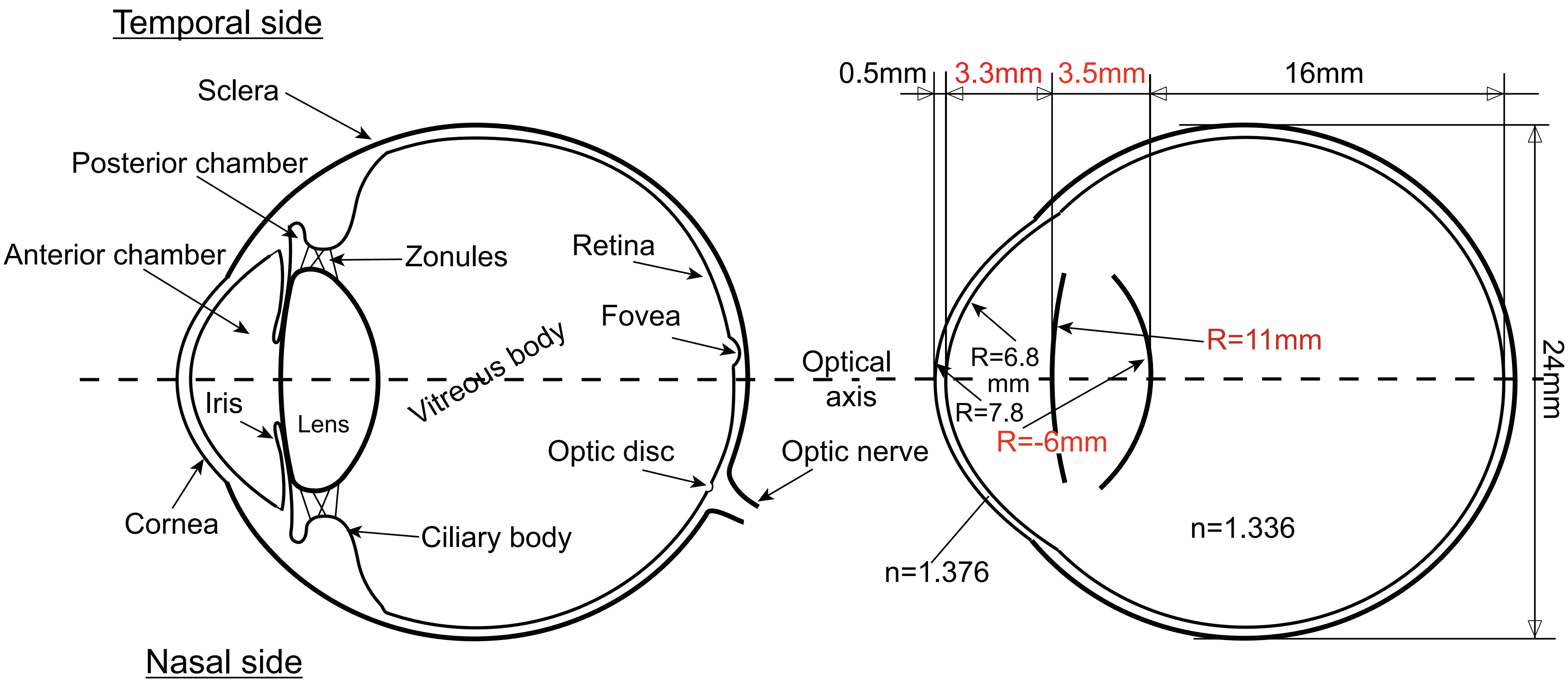
science foundation ireland

Outline

- The aberrated eye
- Adaptive optics and “super-vision”
- Lens replacement in cataract surgery
- Modeling the eye
- Future for improved vision

Anatomy & Optics of the Eye



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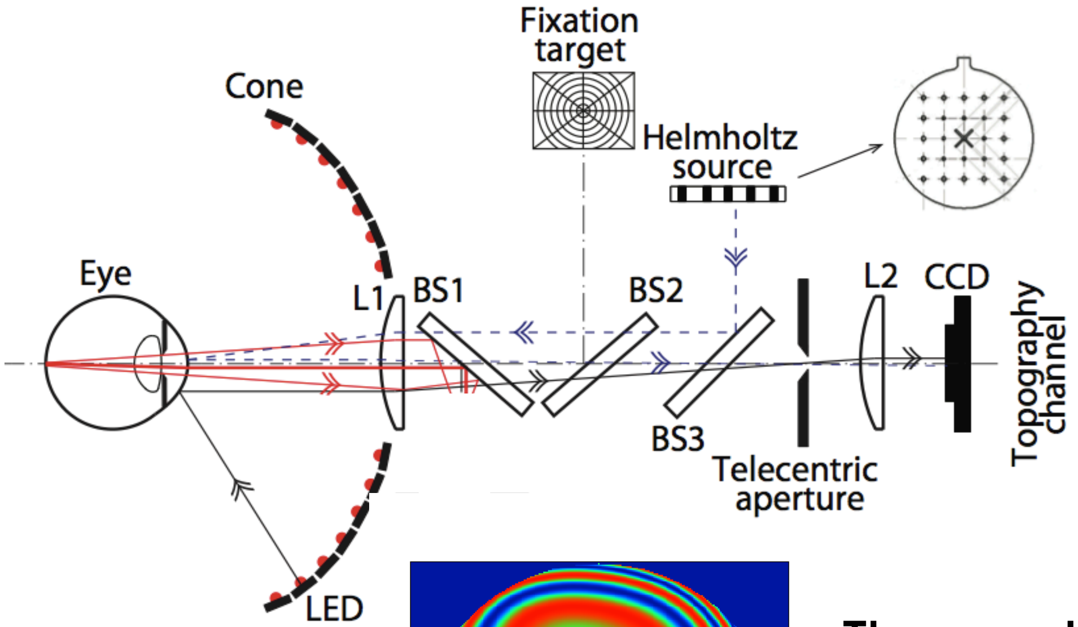
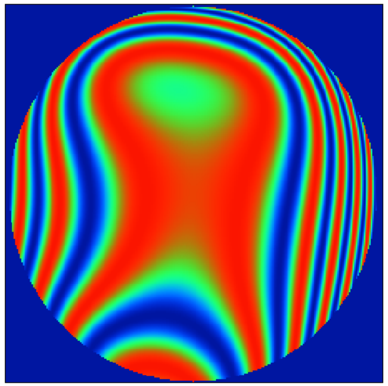
Corneal Topography

Measures the topography of the anterior cornea, which we use in our eye model The corneal map is a result of Hartmann test: imaging LEDs after reflection from the cornea

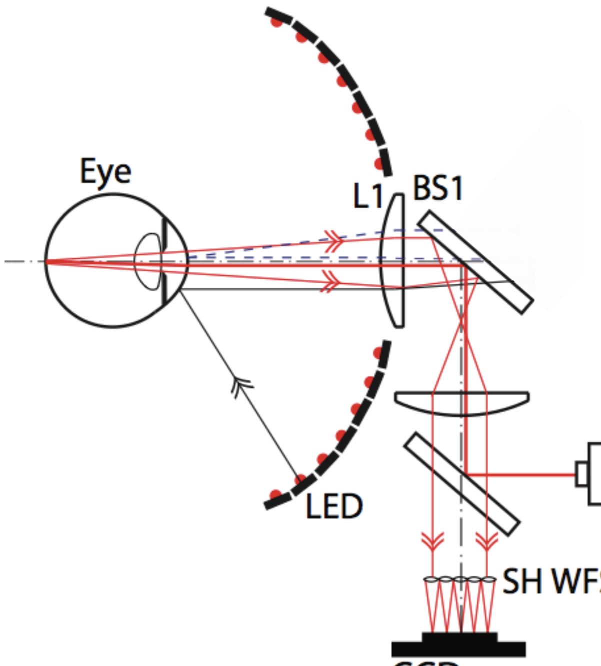


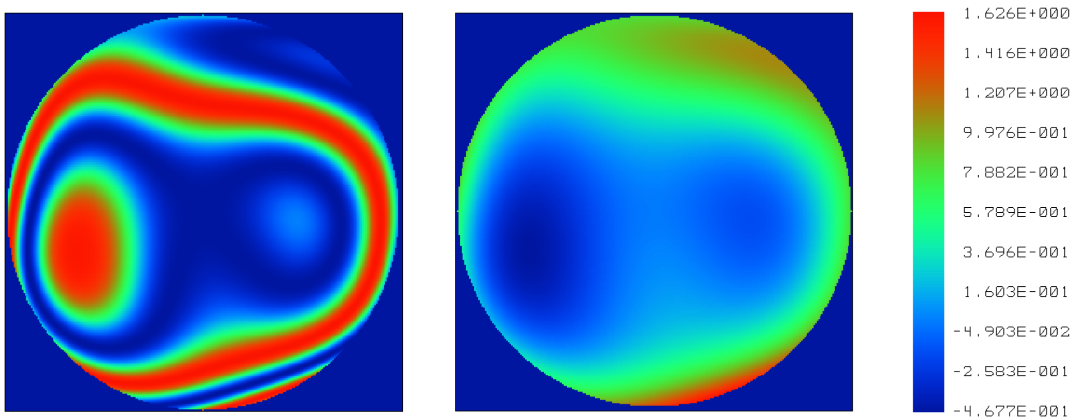


The corneal interferogram shows corneal departure from the best-fit sphere, *r* = 7.8mm
For simplicity 1 fringe = 1 micron

Total Ocular Wavefront

Measures the ocular wavefront emerging from the eye on axis, which we use in our eye model. The wavefront map is obtained by a Shack-Hartmann wavefront sensor





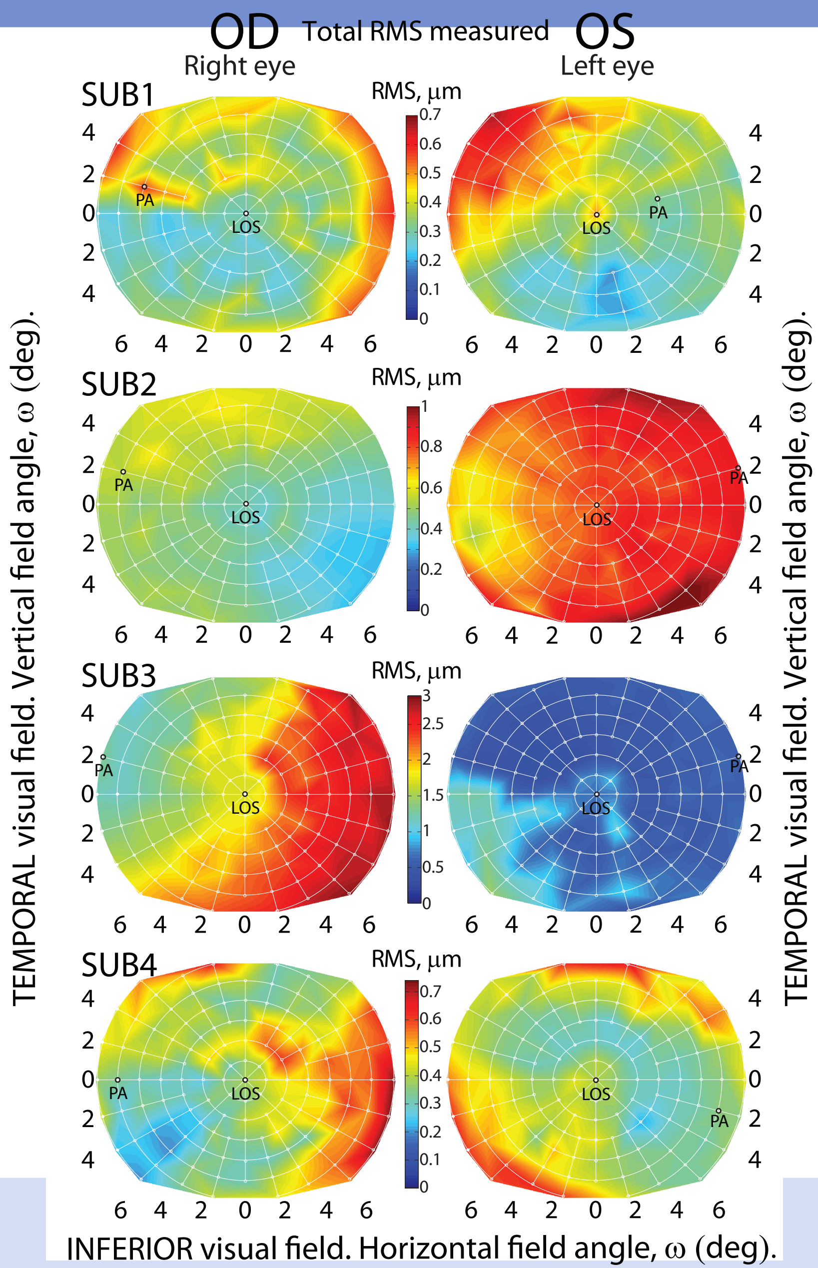
RMS = 0.4 microns

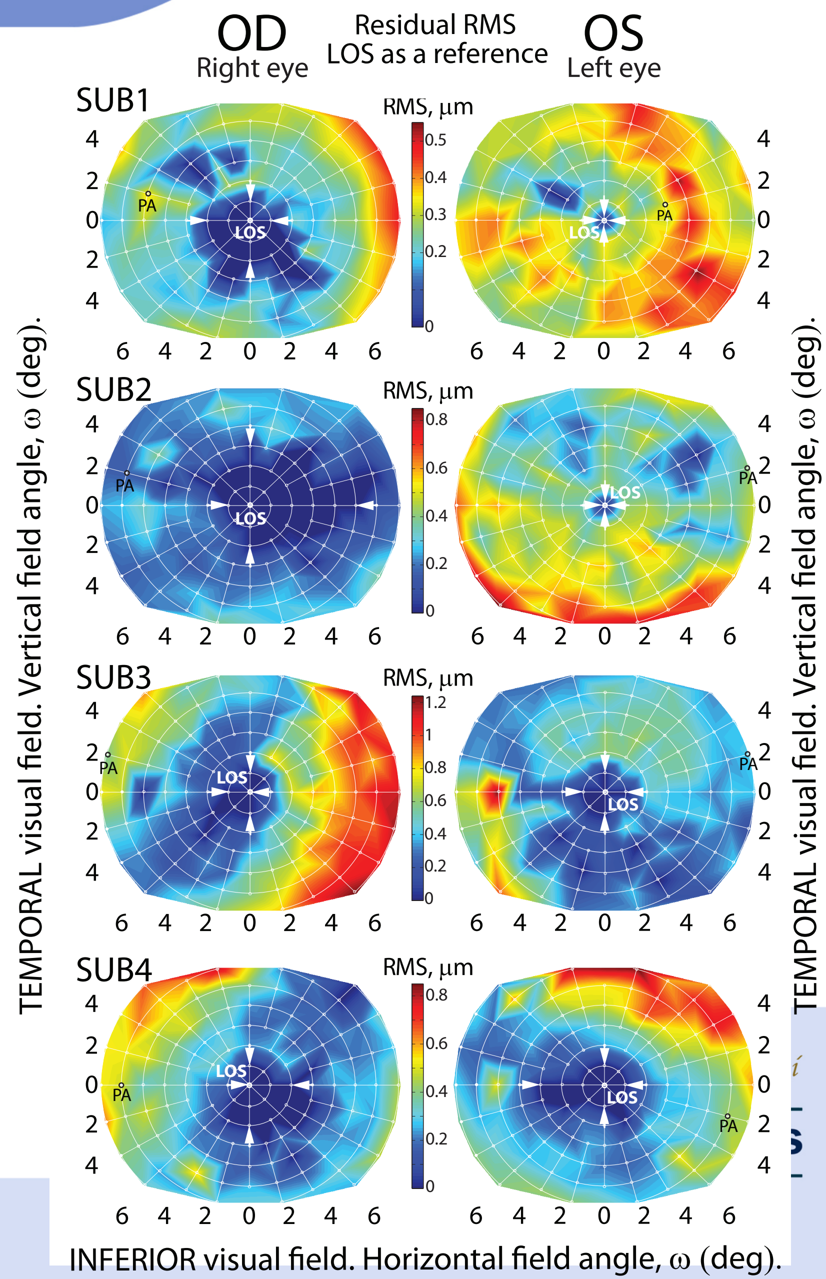
PTV = 2 microns

The interferogram & wavefront map show ocular aberrations in the whole eye on axis
For simplicity 1 fringe = 1 micron

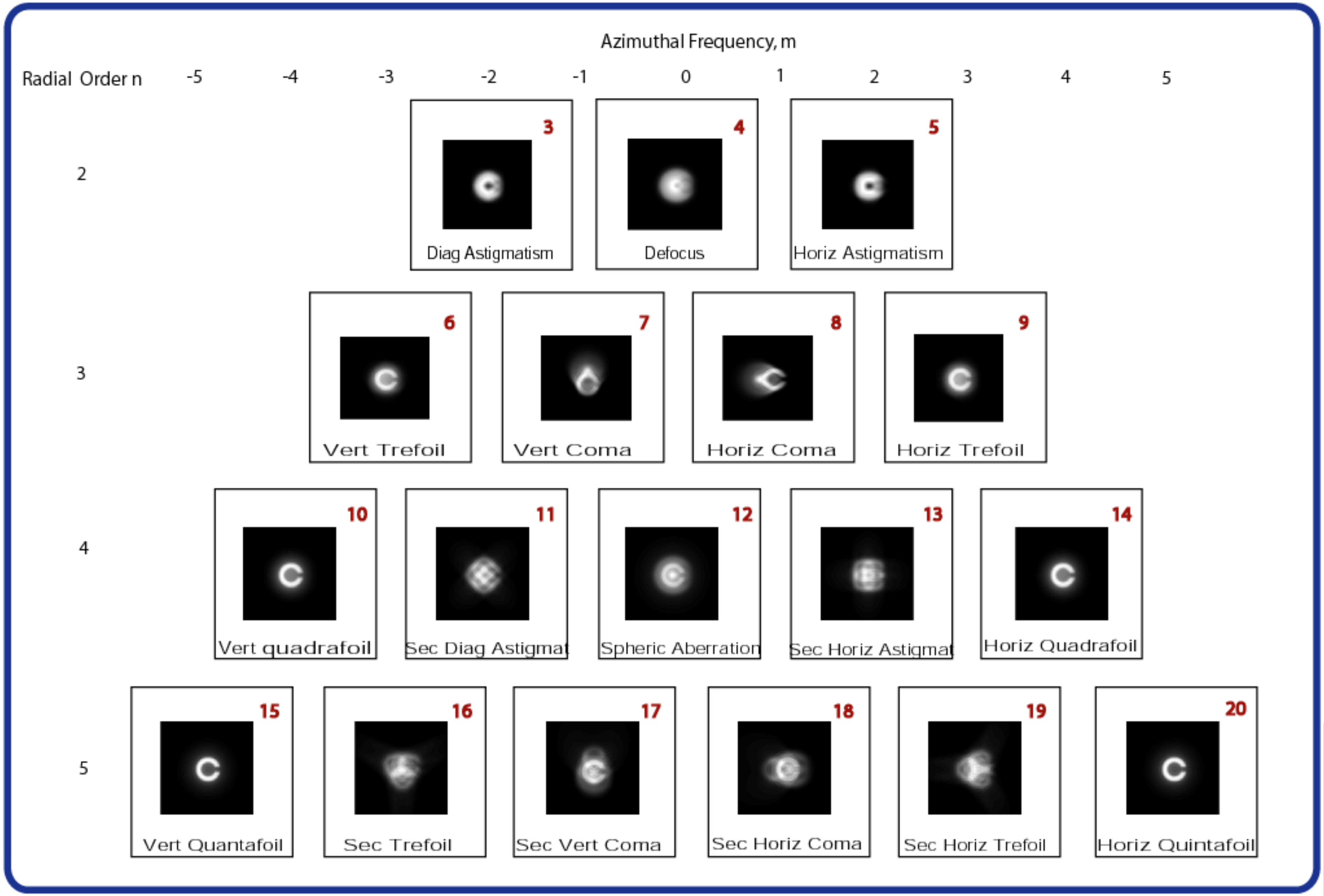
Biomed Optics Express **3** 240-258 (2012)

Isoplanatic Patch

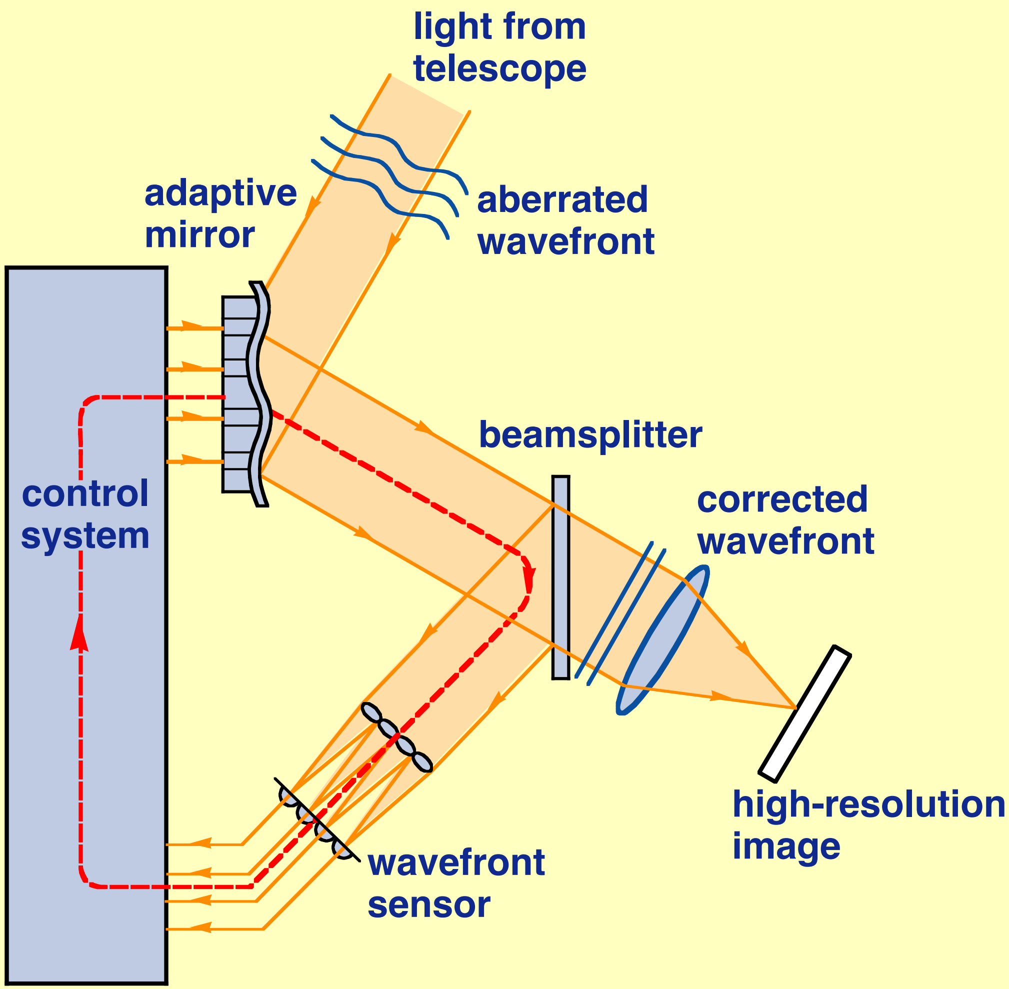




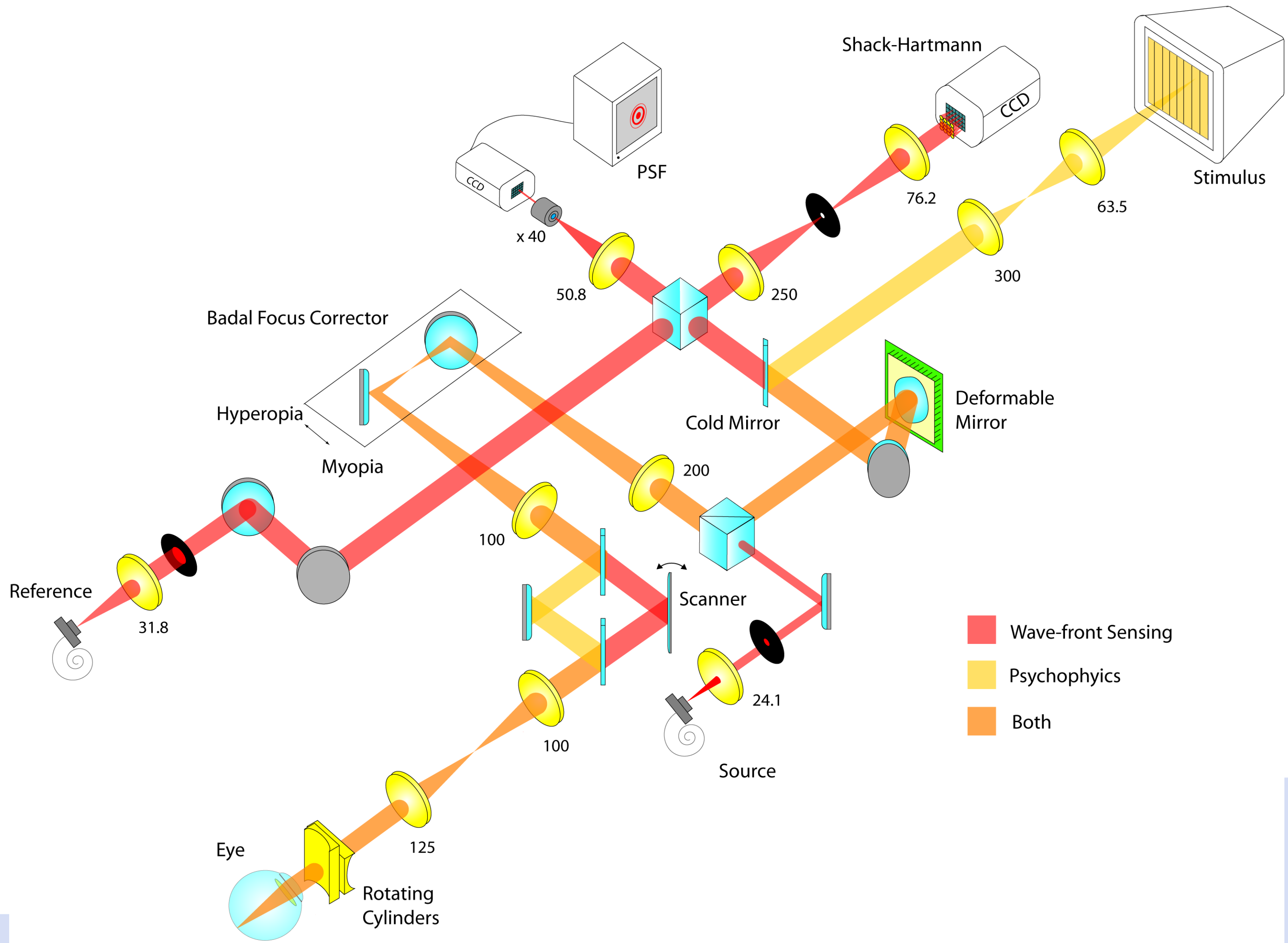
Type of Aberration Matters



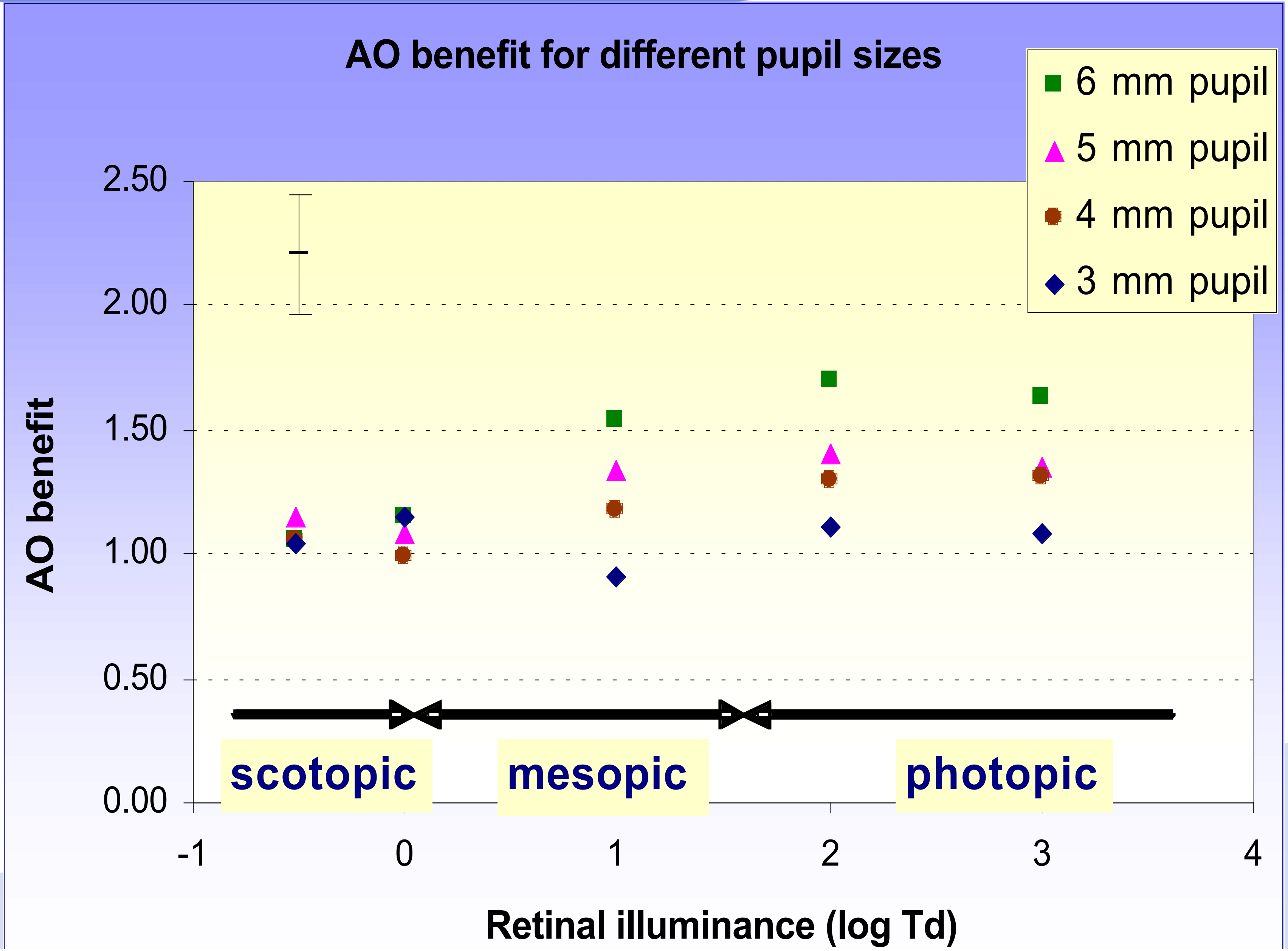
Adaptive Optics



Adaptive Optics Visual Simulator



Is “Super-vision” practical ?

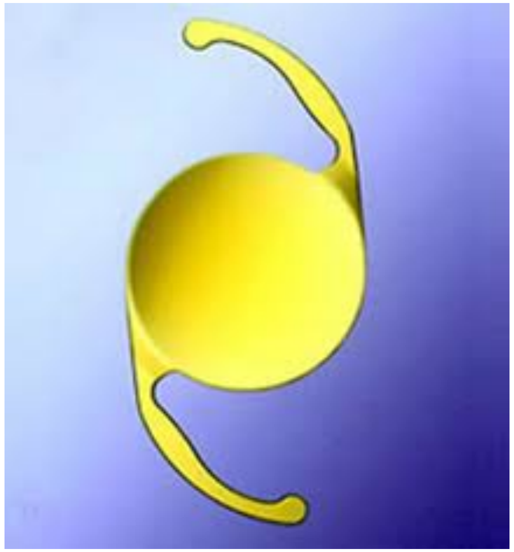


Cataract Surgery

- Most frequently performed surgical procedure, >14M operations per year, number growing due to increased life expectancy

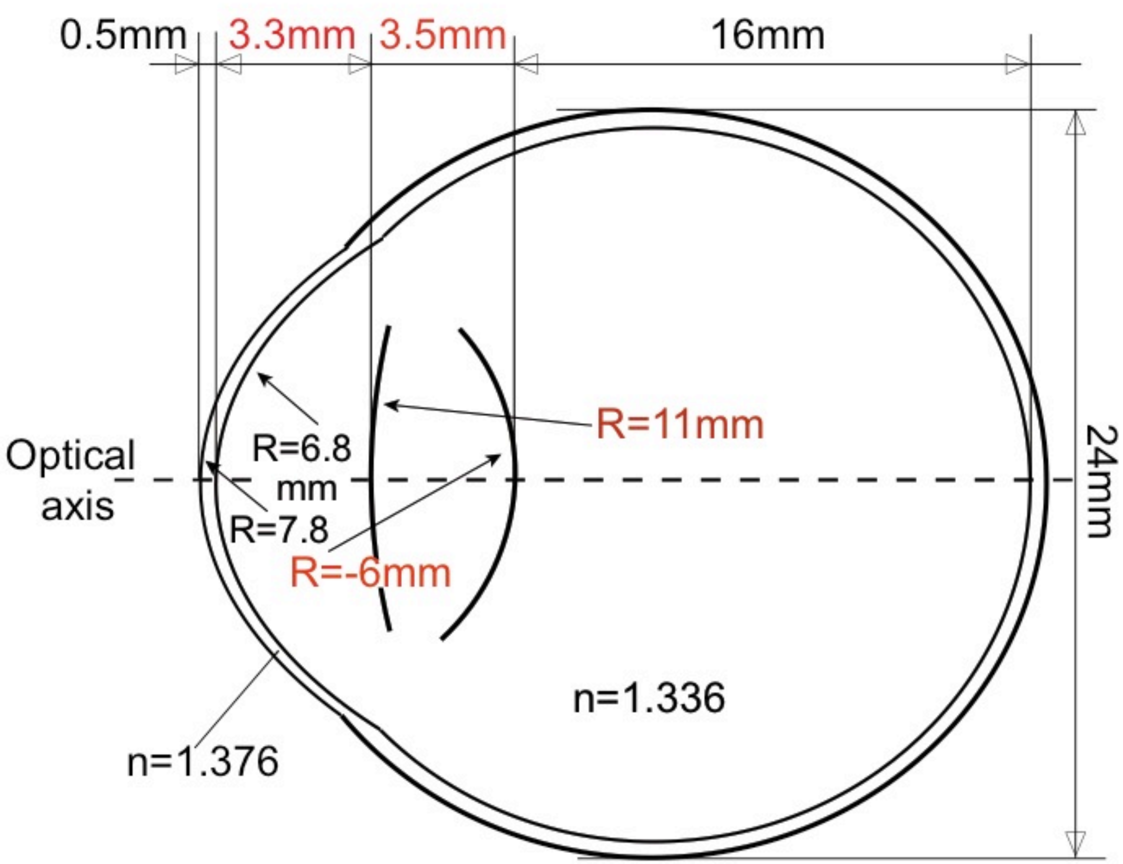
- Cataractous lens removed, plastic intraocular lens (IOL) inserted through ≈2mm incision.

- Optical outcomes excellent (typically 75% with +/-0.5D) in normal eyes, but lower in unusual eyes, e.g. those after LASIK.



- Leading cause of blindness in developing countries, yet curable by relatively simple and safe surgery.

Optics of the Eye



Every number on this figure is incorrect !

Current Methods (example)

- Measure “length” l of eye
- Measure “power” K of cornea
- Use an empirical formula with a regression parameter A

$$P = A - 2.5l - 0.9K$$

P is the power of the IOL

Optical Modeling

The goal is to reconstruct
the optical system of the eye.

Instruments:

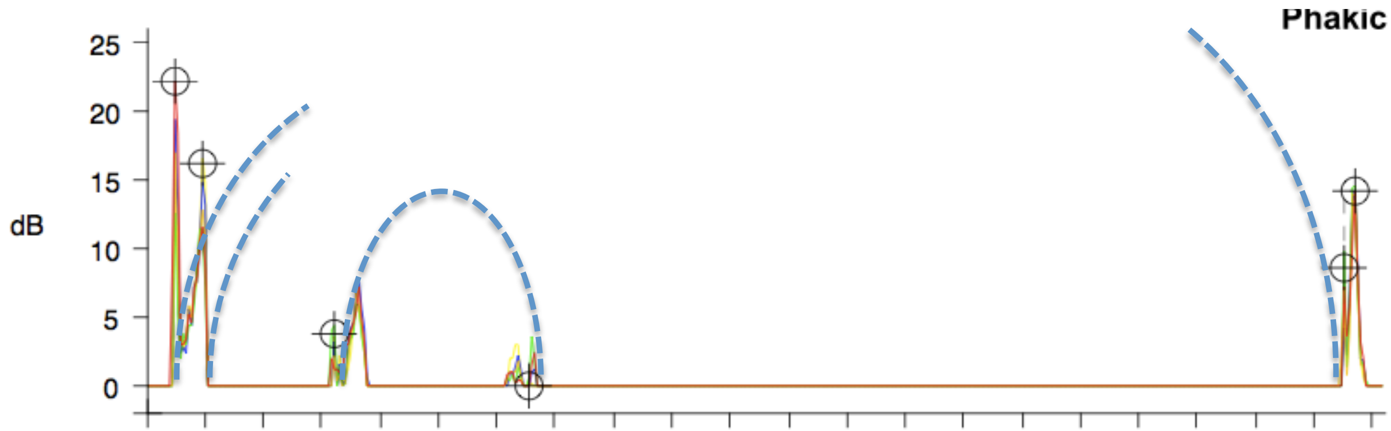
- LensStar (Optical Low-Coherence Reflectometry)
  measures intra-ocular distances
- iDesign (Corneal topographer and wavefront sensor)

Methods:

- Reverse Ray-Tracing
- Wavefront Tomography

Intra-Ocular Distances

LENSTAR provides intra-ocular distances based on 5 measurements, however ideally one would benefit from having raw data (time of flight), e.g. using a custom-made OCT



Measurement	CCT [μm]	AD [mm]	LT [mm]	RT [μm]	AL [mm]
1 (red)	554	2.55	3.89	200**	23.59
2 (yellow)	569	2.56	3.58	200**	23.58
3 (blue)	569	2.57	3.85	200**	23.57
4 (green)	566	2.55	3.86	200**	23.57
5 (orange)	560	2.57	⚠1 ~~0.00~~	200**	23.57
Average	⚠2 **564 μm**	**2.56 mm**	**3.79 mm**	**200** μm**	**23.57 mm**
Standard dev.	6.1	0.010	0.145	0.0	0.007

CCT Cornea thickness
AD Aqueous depth
LT Lens thickness
RT Retina thickness
AL Axial length

* Value user-defined
** System constant
— Value not used

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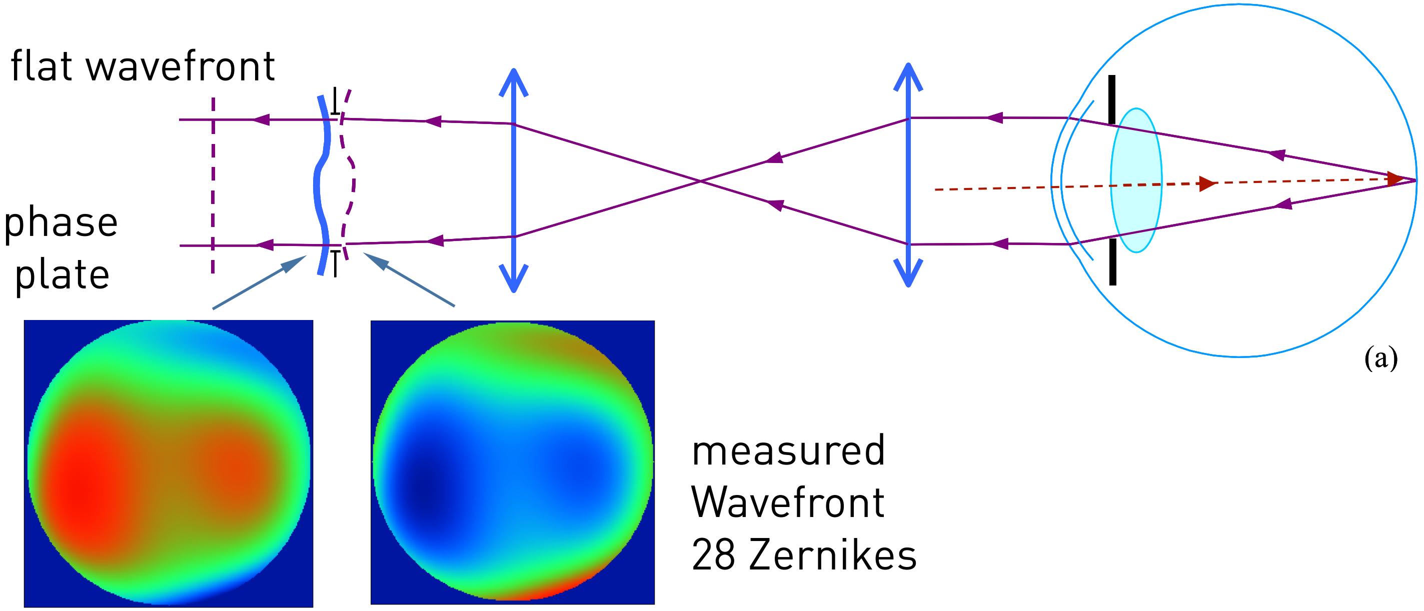
Method: Reverse Ray-Tracing

Reverse ray-tracing is based on reciprocity of light. An aberrated wavefront emerging from the eye is corrected by an imaginary phase plate conjugated to the pupil, as a result we get a flat wavefront. Now tracing rays into the eye model through the phase plate (pre-aberrating the beam) and minimizing the sport size on the retina is the basis for eye reconstruction

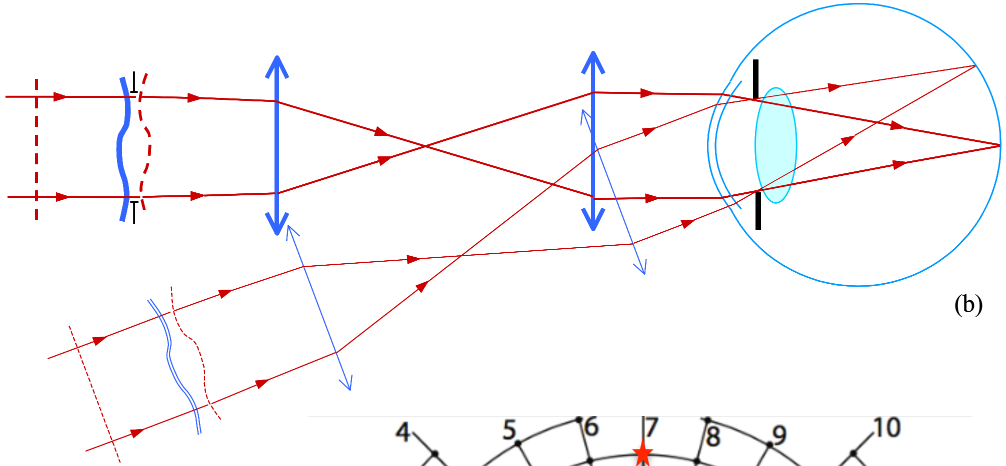


Alexander Goncharov, Maciej Nowakowski, Matthew Sheehan, and Chris Dainty, "Reconstruction of the optical system of the human eye with reverse ray-tracing," Opt. Express 16, 1692-1703 (2008).

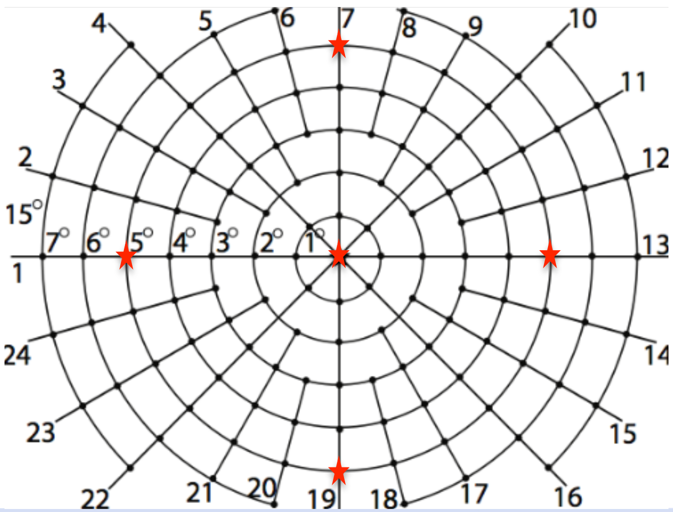
"Inverse Optical Design" – US Patent 7832864

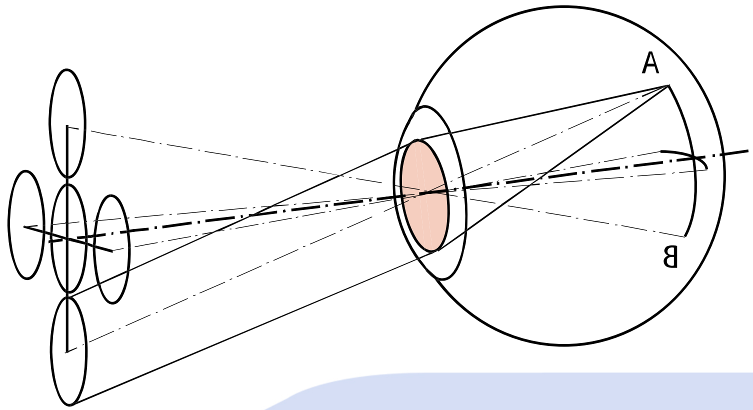
Method: Wavefront Tomography

Wavefront tomography uses several wavefronts measured along different directions in the eye, thus one gets more constrains for reconstructing internal structures. Reverse ray-tracing is applied *simultaneously* for all selected directions (field points)



multi-configuration
eye model





we use 5 points
in the visual field

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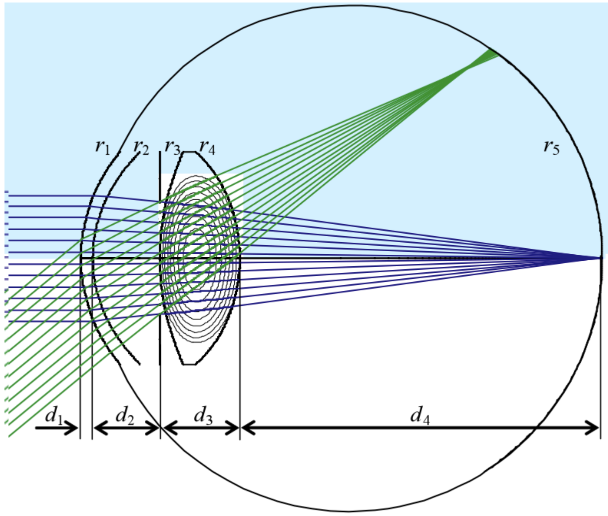
Modeling the Eye: Adaptive GRIN Lens

Adaptive gradient index lens is defined by geometry of its external surfaces, it can operate at wide angles and is suitable for eye & lens reconstruction *in vivo* or *in vitro*
We use it as **a starting design for optimization to reach a patient-specific eye model**



Medium	Radius	Conic constant	Thickness	Refractive index
	r1 = 7.76	c1 = − 0.1		
Cornea			d1 = 0.55	n1 = 1.3721
	r2 = 6.52	c2 = − 0.3		
Aqueous			d2 = 3.06	n2 = 1.33215
	r3 = 11.51	c3 = − 1		
Lens			d3 = 3.69	n3 = 1.361…1.401*
	r4 = − 7.67	c4 = 0.5		
Vitreous			d4 = 16.6	n4 = 1.33224
	r5 = − 12.0	c5= 0		

* Gradient index is defined as a function of the radial distance r and the lens thickness z:

$$n(r,z) = 1.361 - 0.002149r^2 - 0.0000106r^4 + 0.049467z - 0.01596z^2 + 0.0001715z^3 + 0.00141z^4$$

Alexander Goncharov and Chris Dainty, "Wide-field schematic eye models with gradient-index lens," J. Opt. Soc. Am. A 24, 2157-2174 (2007)

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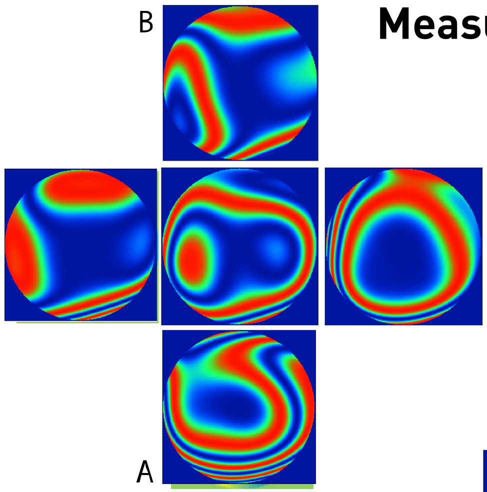
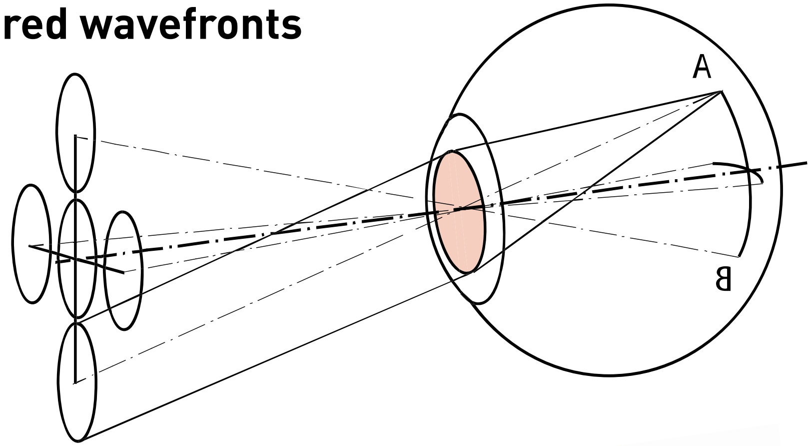
Modeling the Eye: Inverse Optical Design

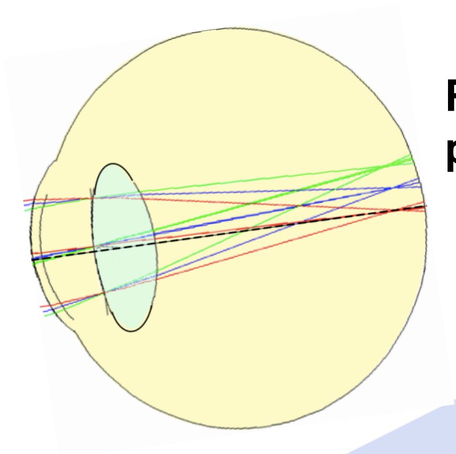
We uses the optical design software Zemax for reverse ray-tracing and optimization of the eye model, so that it predicts well wavefront aberrations at different points in the visual field



Measured wavefronts

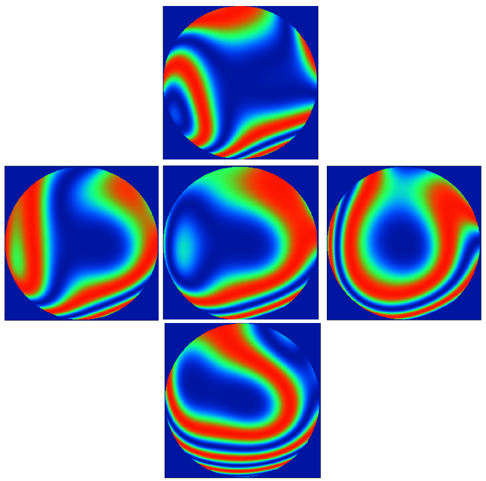


Generic model



Reconstructed patient-specific model

Predicted Wavefronts
RMS diff < λ/4
λ=840nm



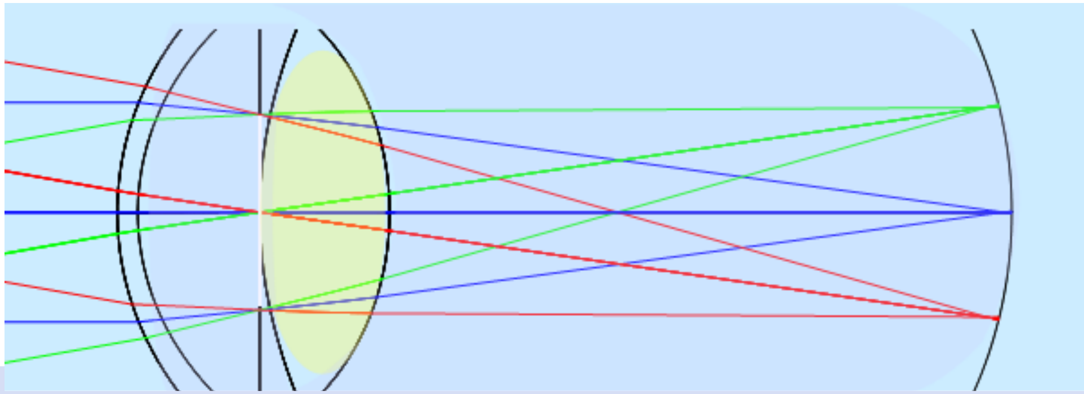
Personalized Eye Model

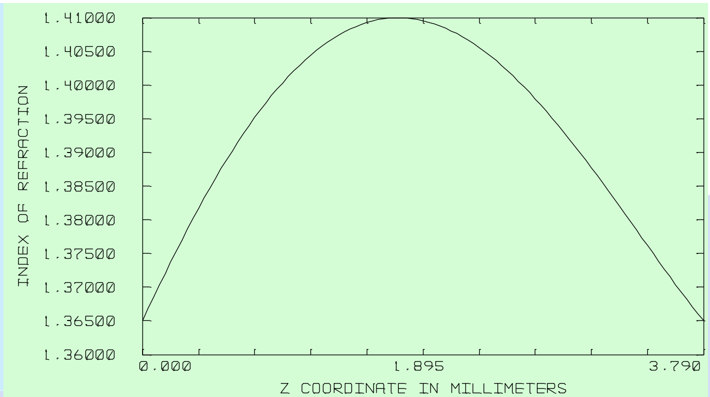
Radius	Conic constant	Thickness	Refractive index	Medium
$r_1 = 7.78$	$c_1 = \text{-}0.1$			
		$d_1 = 0.56$	$n_1 = 1.3721$	cornea
$\boldsymbol{r_2 = 6.52}$*	$\boldsymbol{c_2 = -0.1}$			
		$d_2 = 2.56$	$n_2 = 1.33215$	aqueous
$\boldsymbol{r_3 = 11.2}$	$\boldsymbol{c_3 = -1}$			
		$d_3 = 3.79$	$\boldsymbol{n_3 = 1.365\ldots1.41}$**	lens
$\boldsymbol{r_4 = -6.4}$	$\boldsymbol{c_4 = -0.12}$			
		$d_4 = 16.66$	$n_4 = 1.33224$	vitreous
$\boldsymbol{r_5 = -11.5}$	$\boldsymbol{c_5 = 1}$			

*All variables are shown in **bold**

**Gradient index is defined as a function of the radial distance *r* and the lens thickness *z*

$$n(r,z) = 1.365 - 0.002135r^2 - 0.000002r^4 + 0.04777z - 0.079748z^2 - 0.003868z^3 + 0.000698z^4$$





Future for Improved Cataract Surgery

- Personalised eye modeling
- Customised intra-ocular lenses and/or post-operative "trimming".
- Optically perfect imaging

Acknowledgements

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