Centre de Desenvolupament de Sensors, Instrumentació i Sistemes
Departament d'Òptica i Optometria
UNIVERSITAT POLITÈCNICA DE CATALUNYA

Curvature sensing: a new method for ocular wave-front determination

Curvature sensing: a new method for ocular wave-front determination

F. Díaz-Doutón, S.O. Luque, V. Lapuente, M. Arjona, J. Pujol, F. Sanabria

3rd European Meeting in Physiological Optics

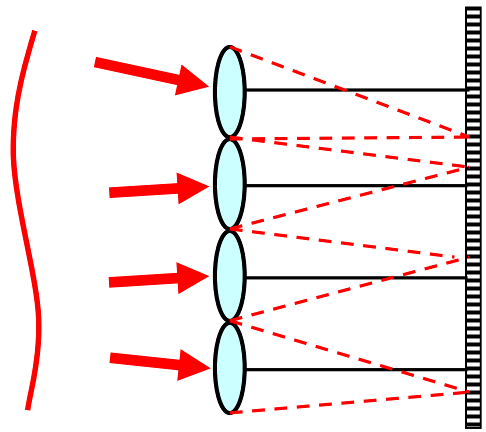
London, september 2006

Current ocular wave-front sensors are based on sampling the slope of the wave-front across the pupil

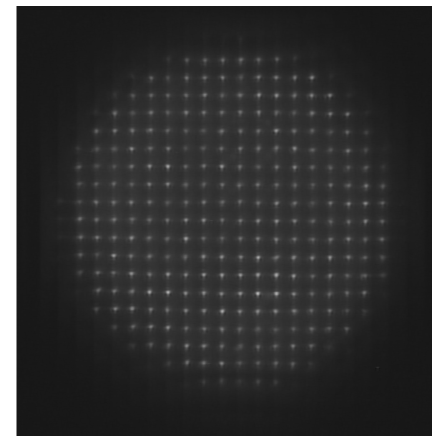
Example: Hartmann-Shack sensor

WA

Microlens array



HS image



$$\Delta x_i \propto \frac{\partial WA(x_i, y_i)}{\partial x}$$

$$\Delta y_i \propto \frac{\partial WA(x_i, y_i)}{\partial y}$$

Fit to Zernike polynomials

DRAWBACK

The number of samples limits the aberration order that can be achieved in the reconstruction !

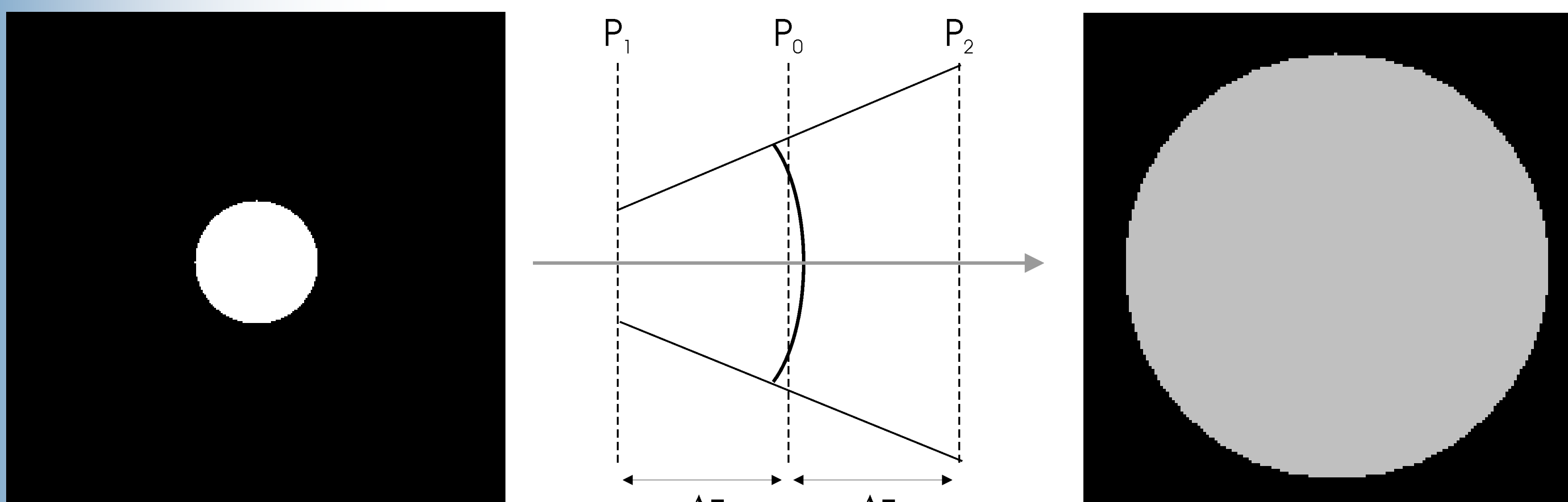
Important when high order aberrations are significant*

*** F. Diaz-Douton et al., "Comparison of the retinal image quality with a Hartmann-Shack sensor and a double-pass instrument", IOVS 47, 1710-6 (2006)**

ALTERNATIVE

Curvature sensor

Based on the changes in light intensity as it travels through its optical path



Irradiance Transport Equation:

$$k\frac{\partial}{\partial z}I(r,z) = -\nabla\left[I(r,z)\nabla\varphi(r,z)\right]$$

Linear approximation

$$\frac{\partial}{\partial z}I(r,z) \approx \frac{I(r,z_1)-I(r,z_2)}{2\Delta z}$$

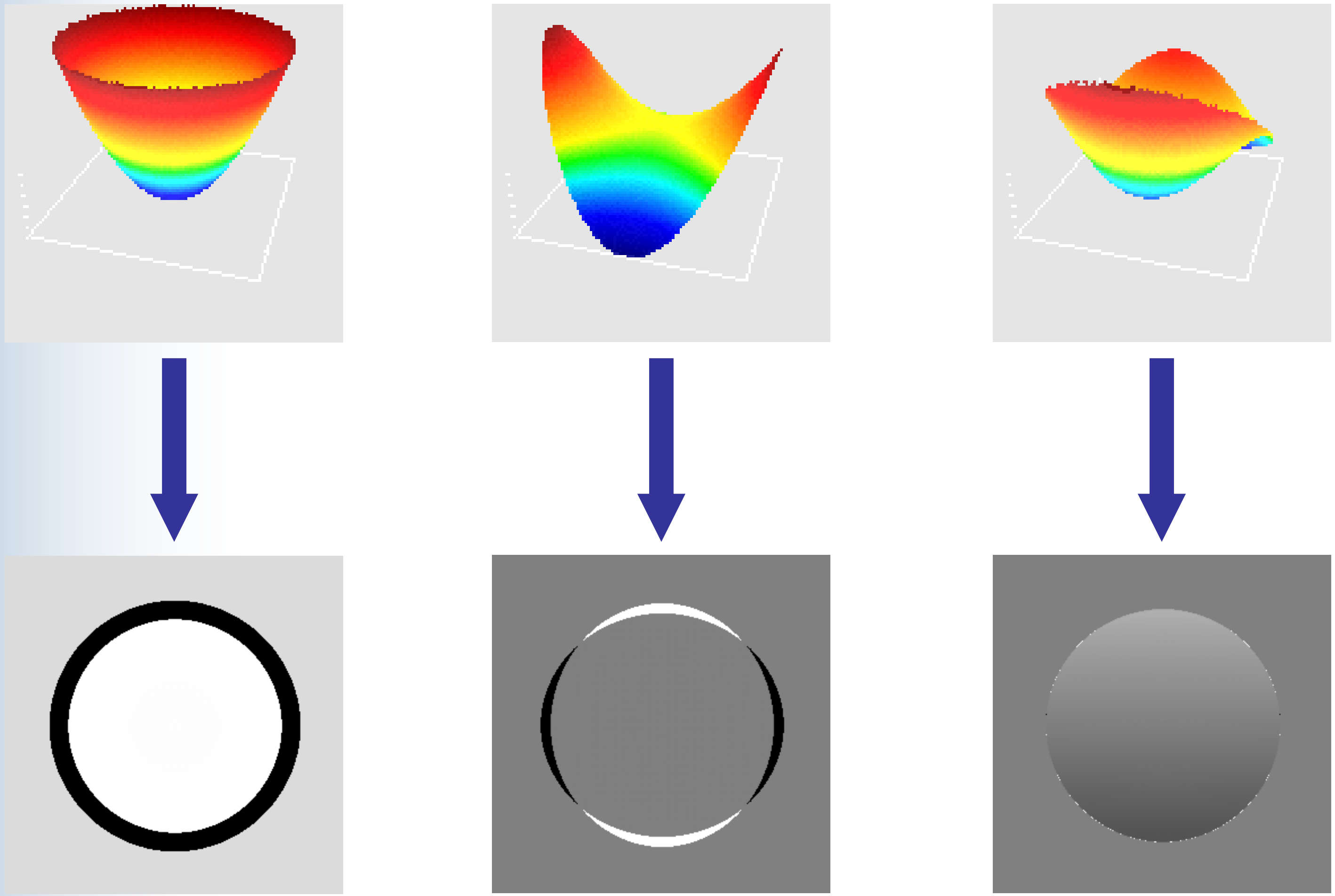
$$\frac{I_1 - I_2}{I_1 + I_2} = -\frac{\Delta z}{k}\left[\nabla^2\varphi(r,z_0) + \delta(e)\frac{\partial}{\partial \mathbf{n}}\varphi(r,z_0)\right]$$

Contrast between images in two planes
Sensor's signal (*S*)

Wave-front's curvature

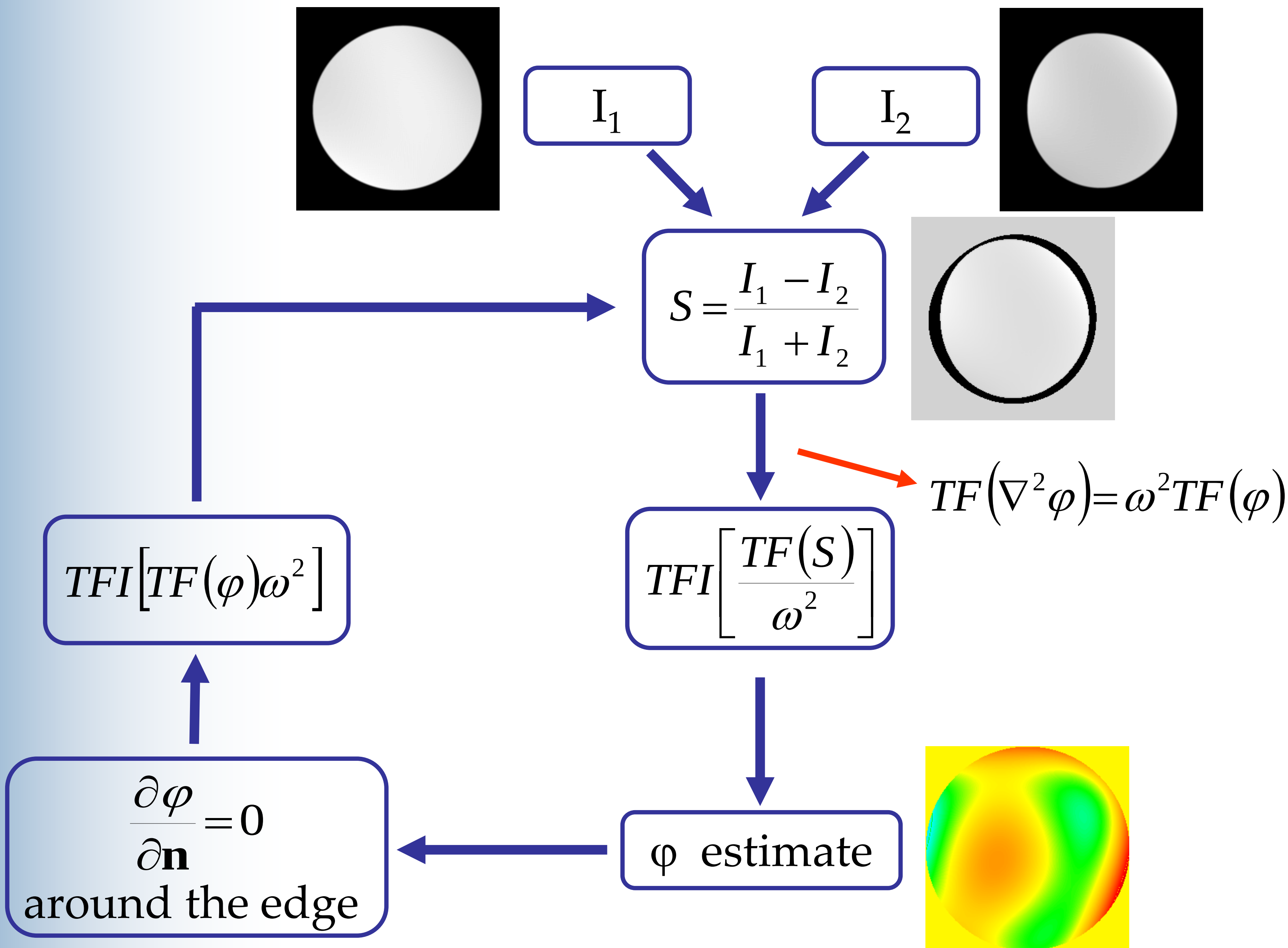
Wave-front's first derivative
(Only on the signal's edge)

Examples of *S*:



Defocus (Z_2^0) | Astigmatism (Z_2^2) | Coma (Z_3^{-1})

Iterative Fourier Transform algorithm



Advantages:

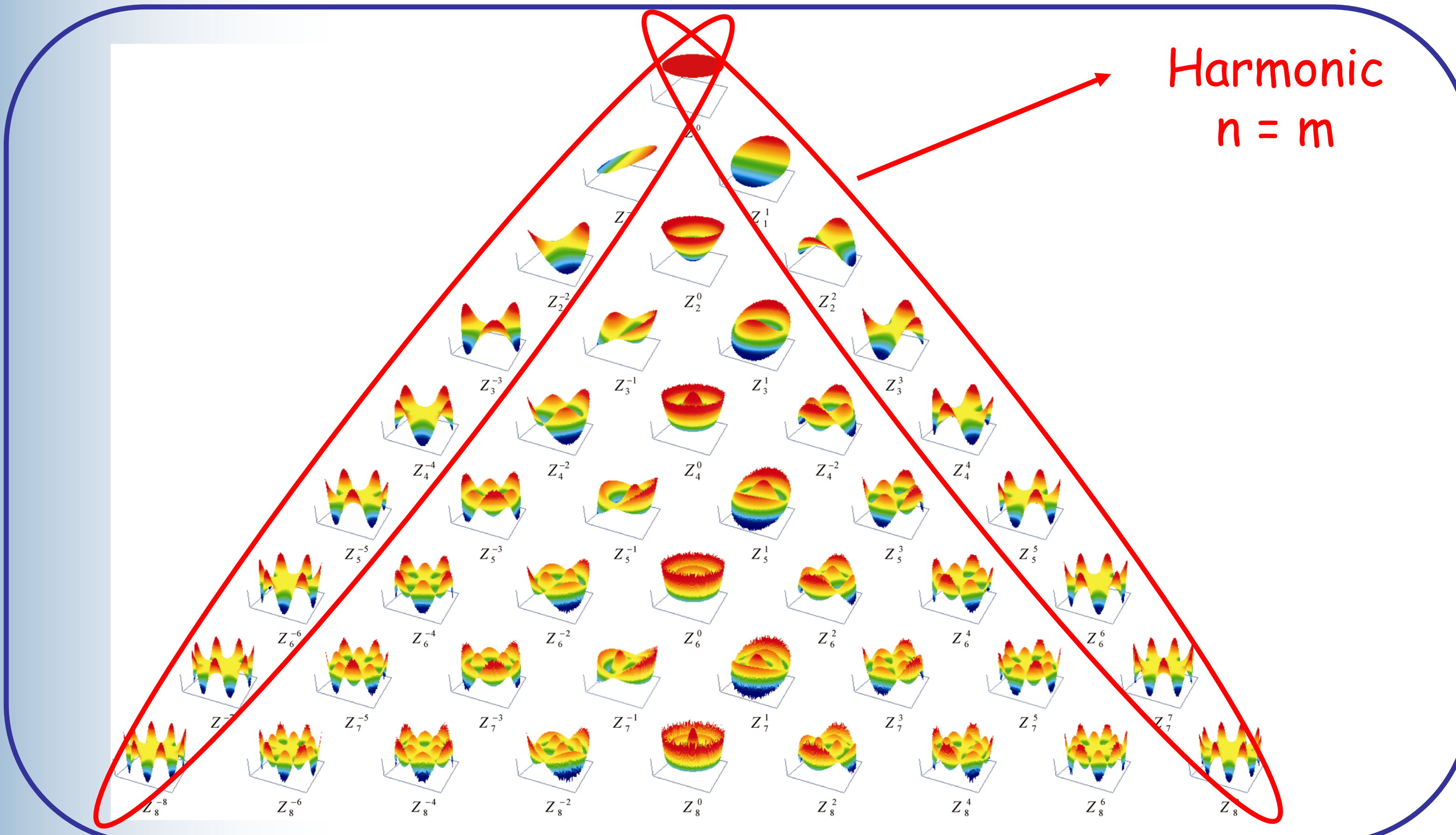
- A higher aberration order can be retrieved
- Much higher dynamic range for low order aberrations
- Is possible to retrieve information within pupil zones with reduced transmitance
- Application in very high frequency closed-loop adaptive optics systems
- Much cheaper

Numerical simulations:

- Optimal placement of the detection planes
- Performance of the wave-front retrieval algorithm
- Optical system design
  - System's aberrations
  - Sensitivity
  - Dynamic range
- Noise

Wave-front retieval algorithm:

Problem: **The second derivative is equal to zero for the harmonic modes**

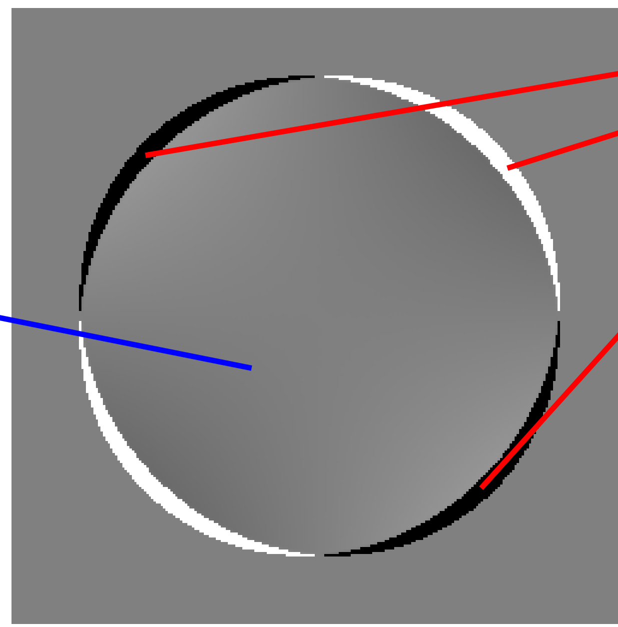


Wave-front retieval algorithm:

Classic solution: Imposing boundary conditions

New solution: Separate the signal in two different zones and treat them independently

S



EZ

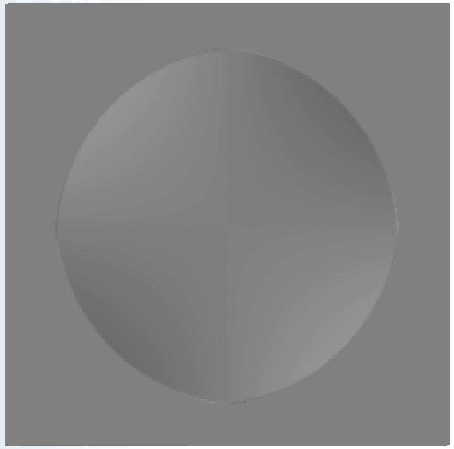
Information on wave-front's first derivative

OZ

Information on wave-front's second derivative

Wave-front retieval algorithm:

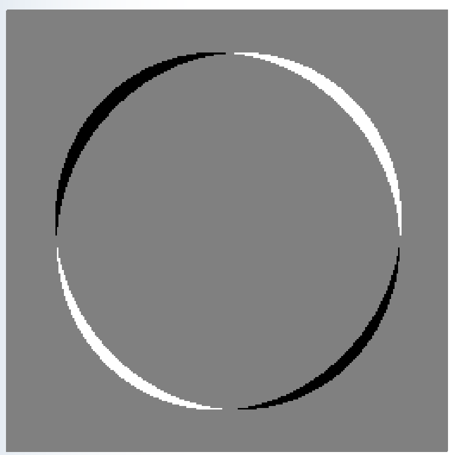
OZ



$$TFI\left[\frac{TF(ZS)}{\omega^2}\right]$$

→ Contribution of non-harmonic modes

EZ

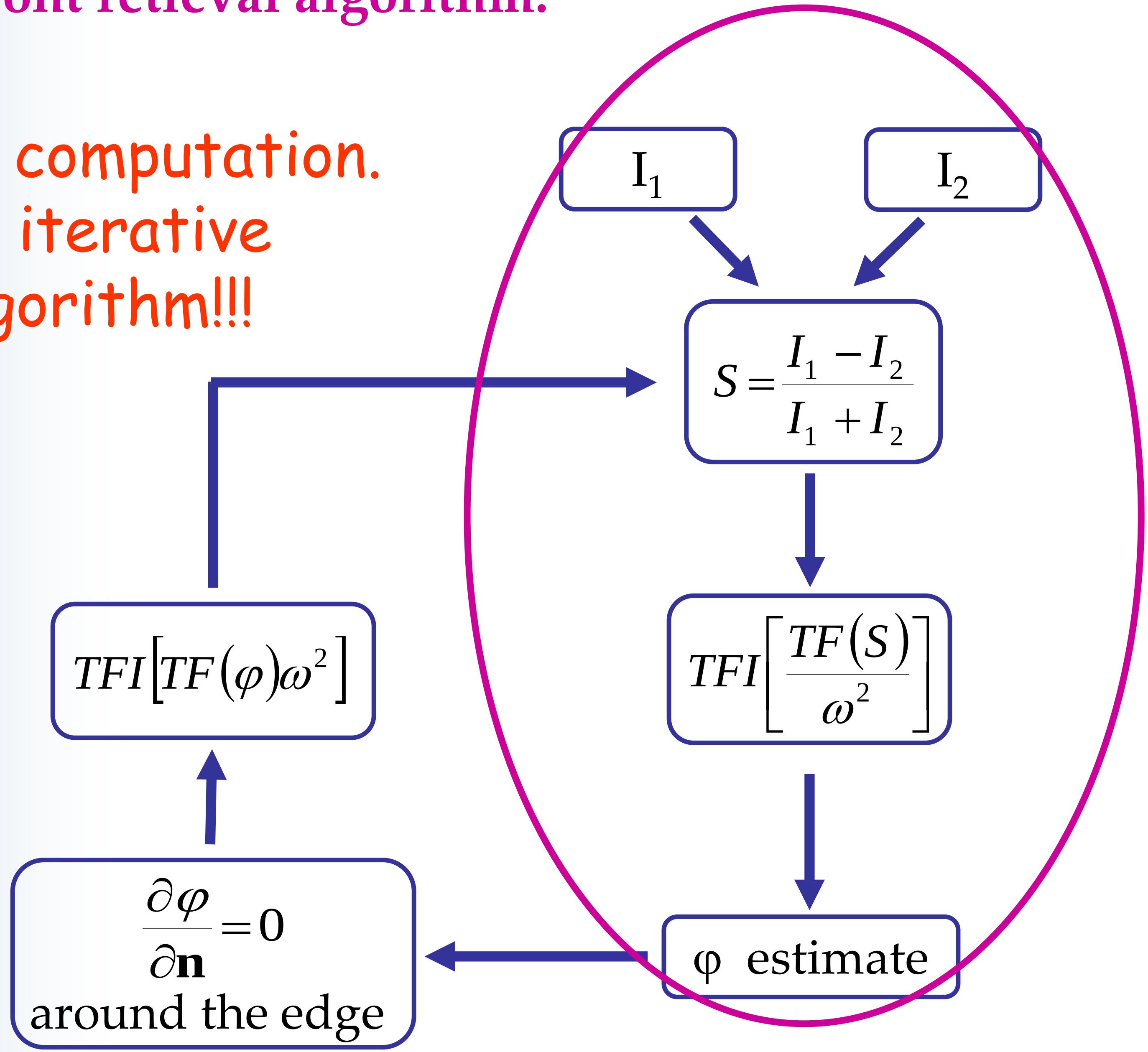


$$TFI\left[\frac{TF(ZE)}{\omega^2}\right]$$

→ Contribution of harmonic modes

Wave-front retieval algorithm:

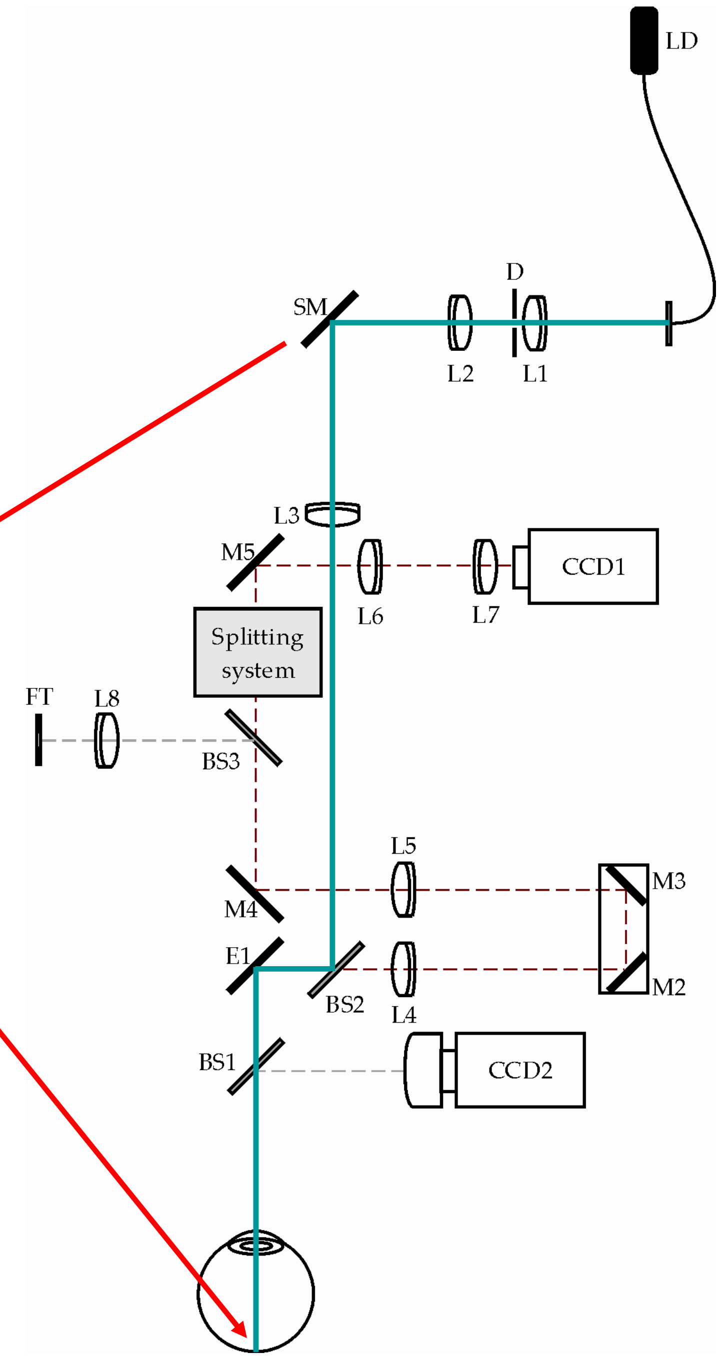
Direct computation.
No iterative algorithm!!!



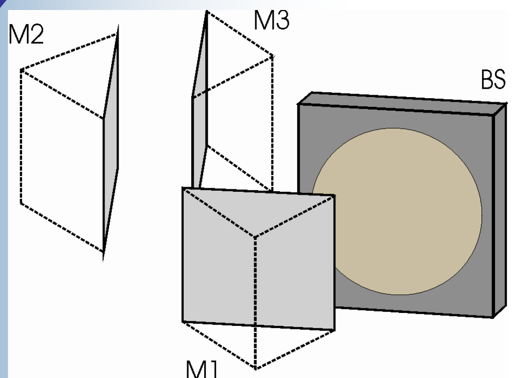
Optical set-up:

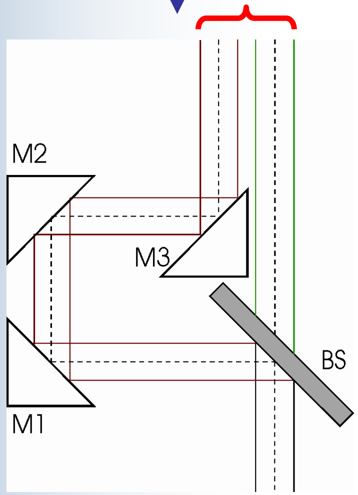
Spinning mirror

Scans the position of the beam on the retina



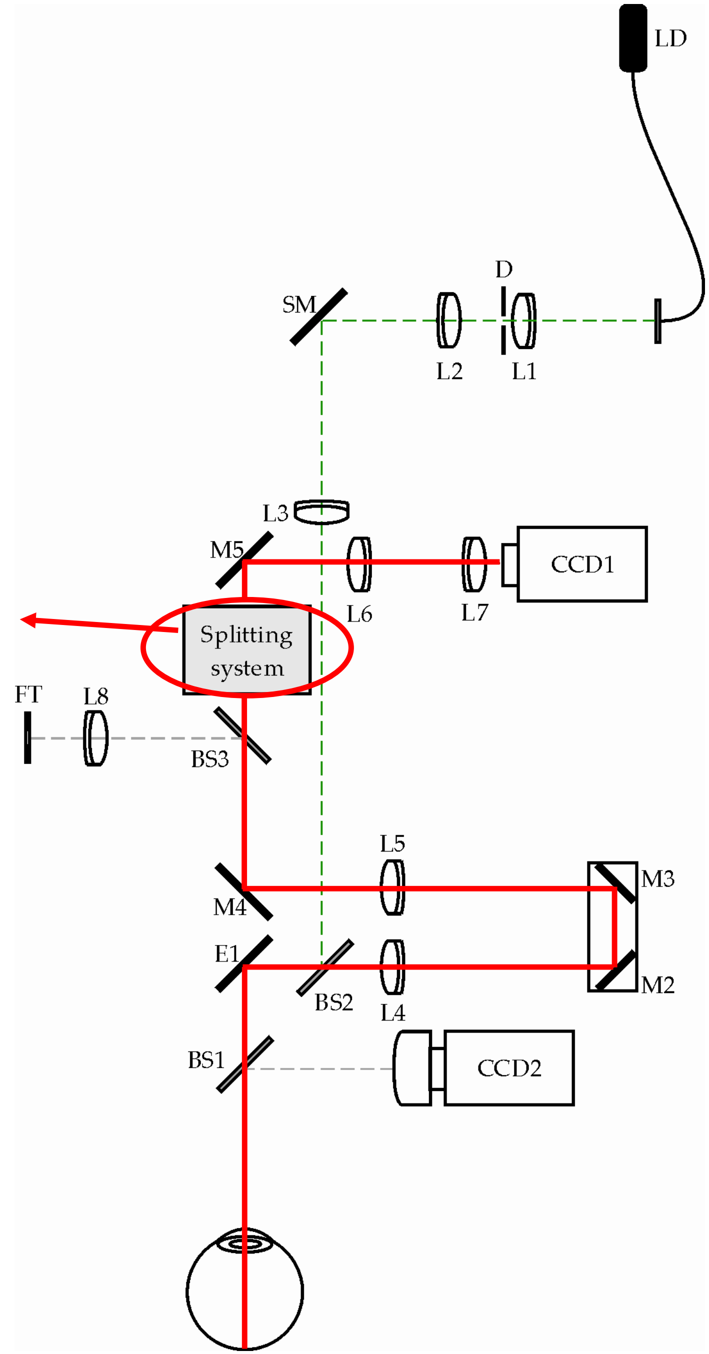
Optical set-up:





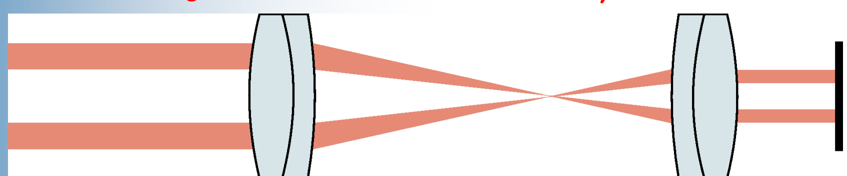
Lateral displacement: 10 mm

Optical path difference: 33 mm

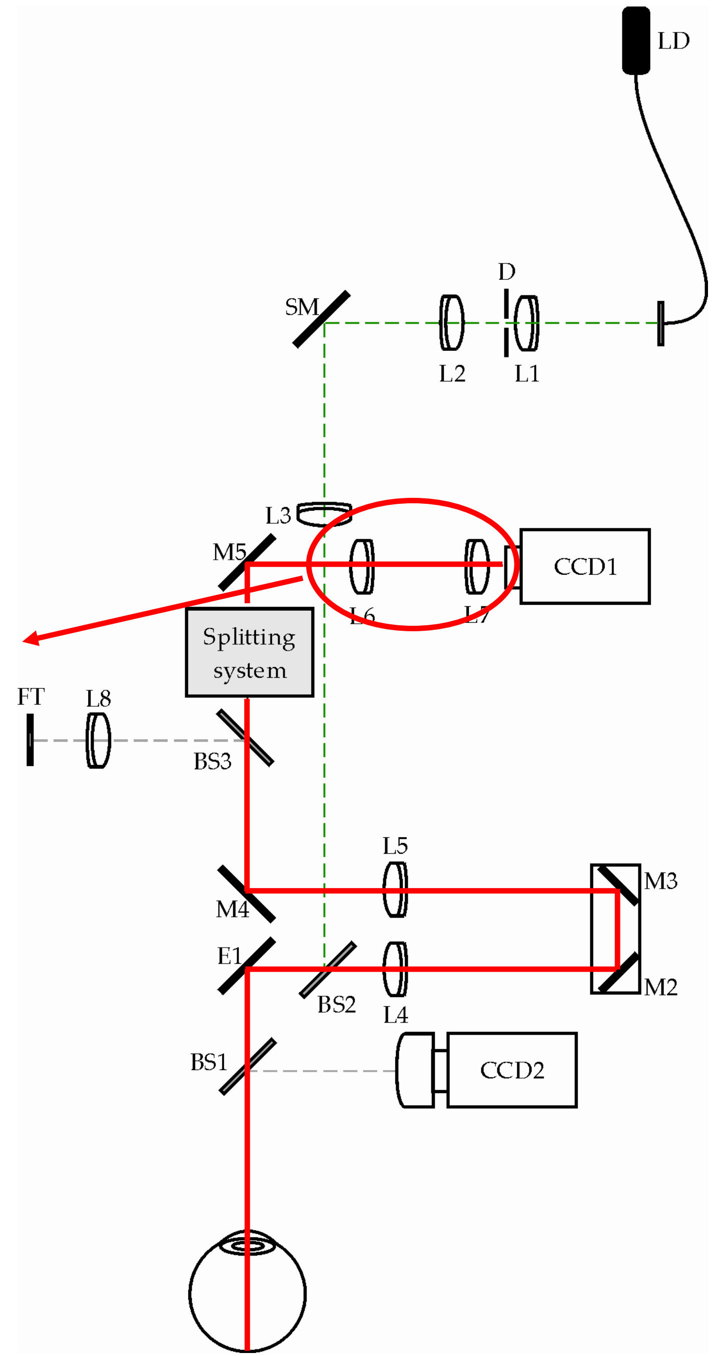


Optical set-up:

f_6 = 75 mm f_7 = 25.4 mm



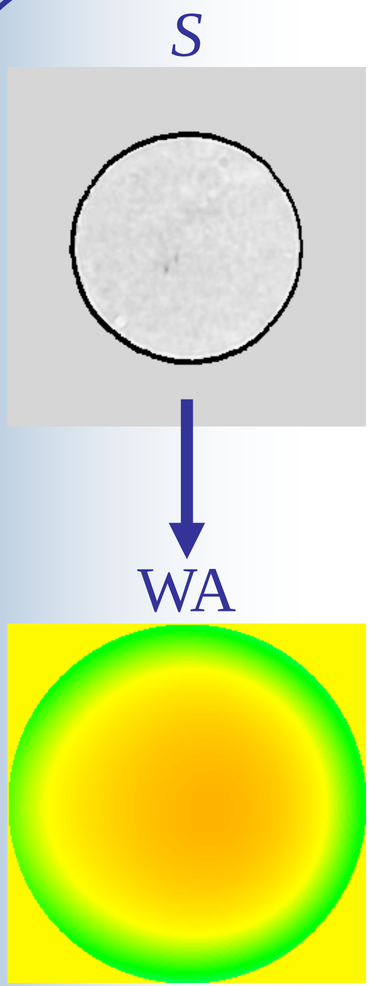
Both images registered at once by the camera

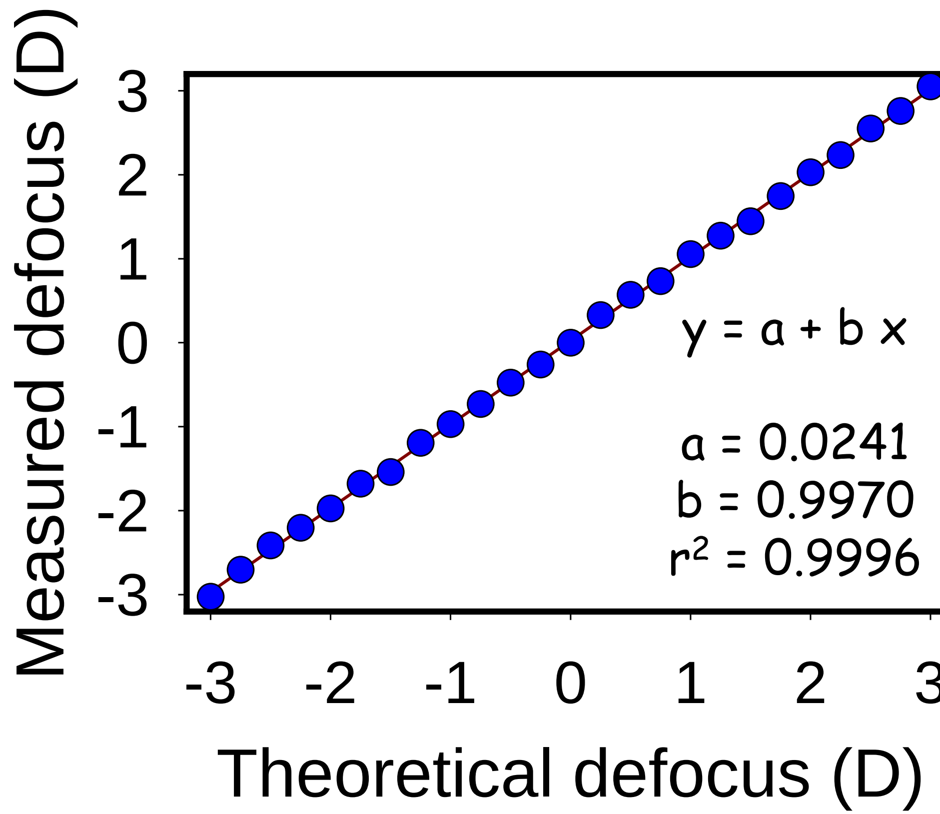


Experimental results:

Calibration:

Spherical lenses

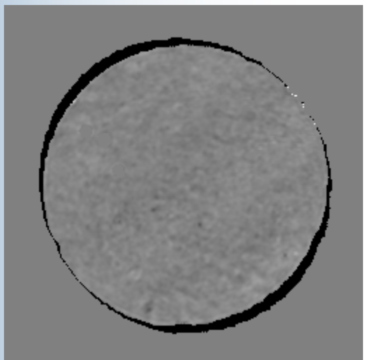




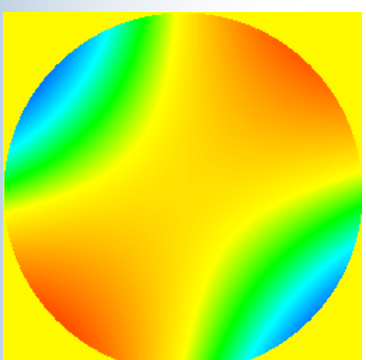
Experimental results:

Calibration:

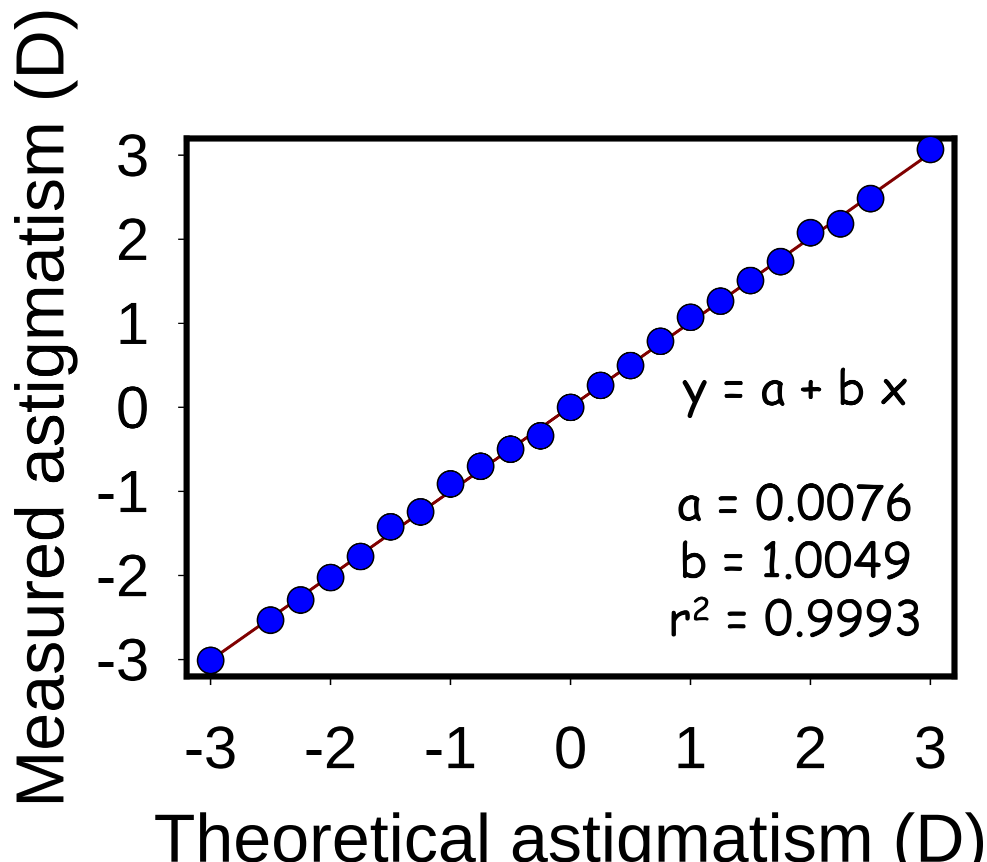
S



WA



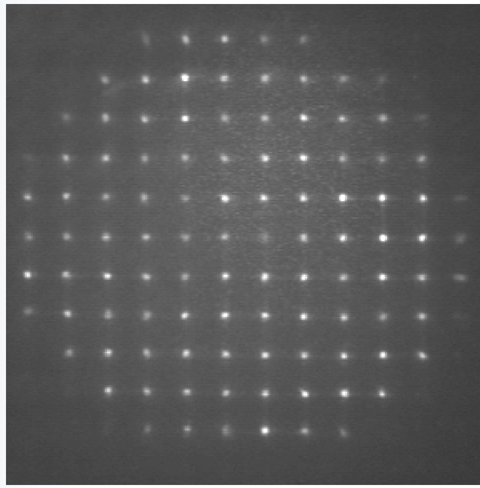
Cylindrical lenses

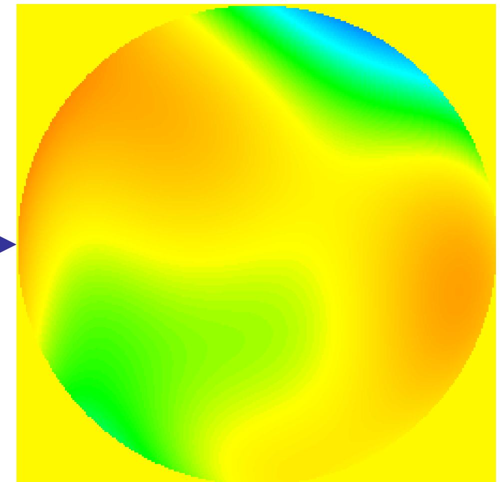


Experimental results:

Real eye's measurements:

H-S

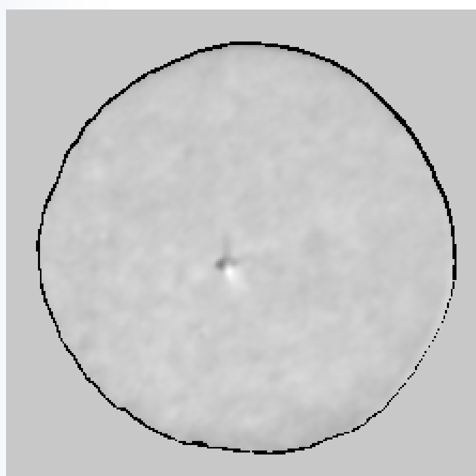


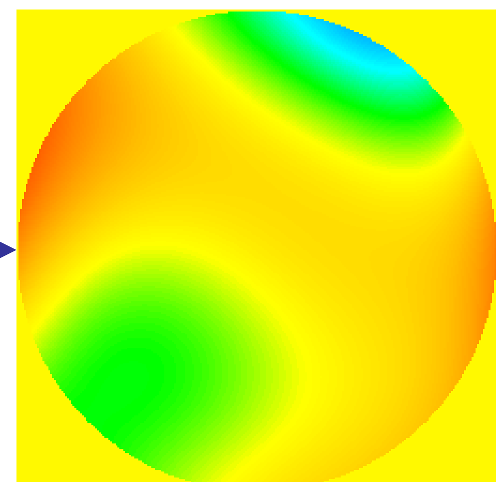


RMS

0.396 ± 0.012 μm

Curvature





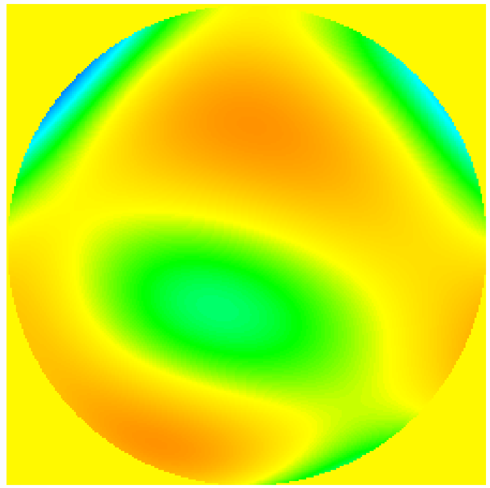
RMS

0.365 ± 0.043 μm

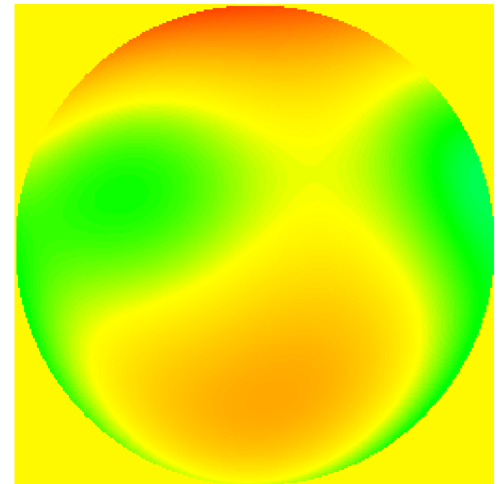
Experimental results:

Real eye's measurements:

H-S

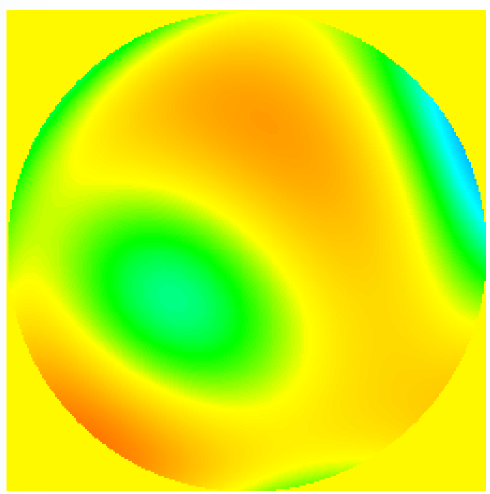


RMS 0.430 μm

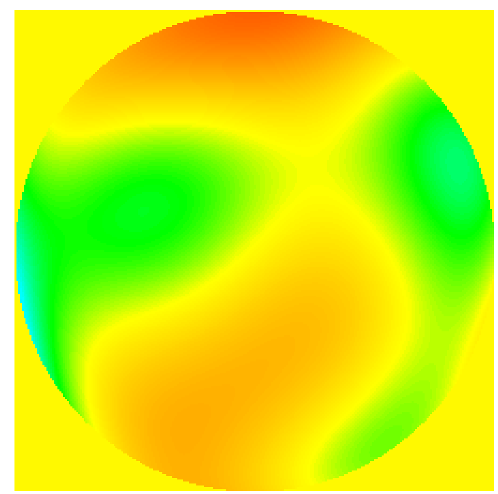


RMS 0.396 μm

Curvature



RMS 0.416 μm



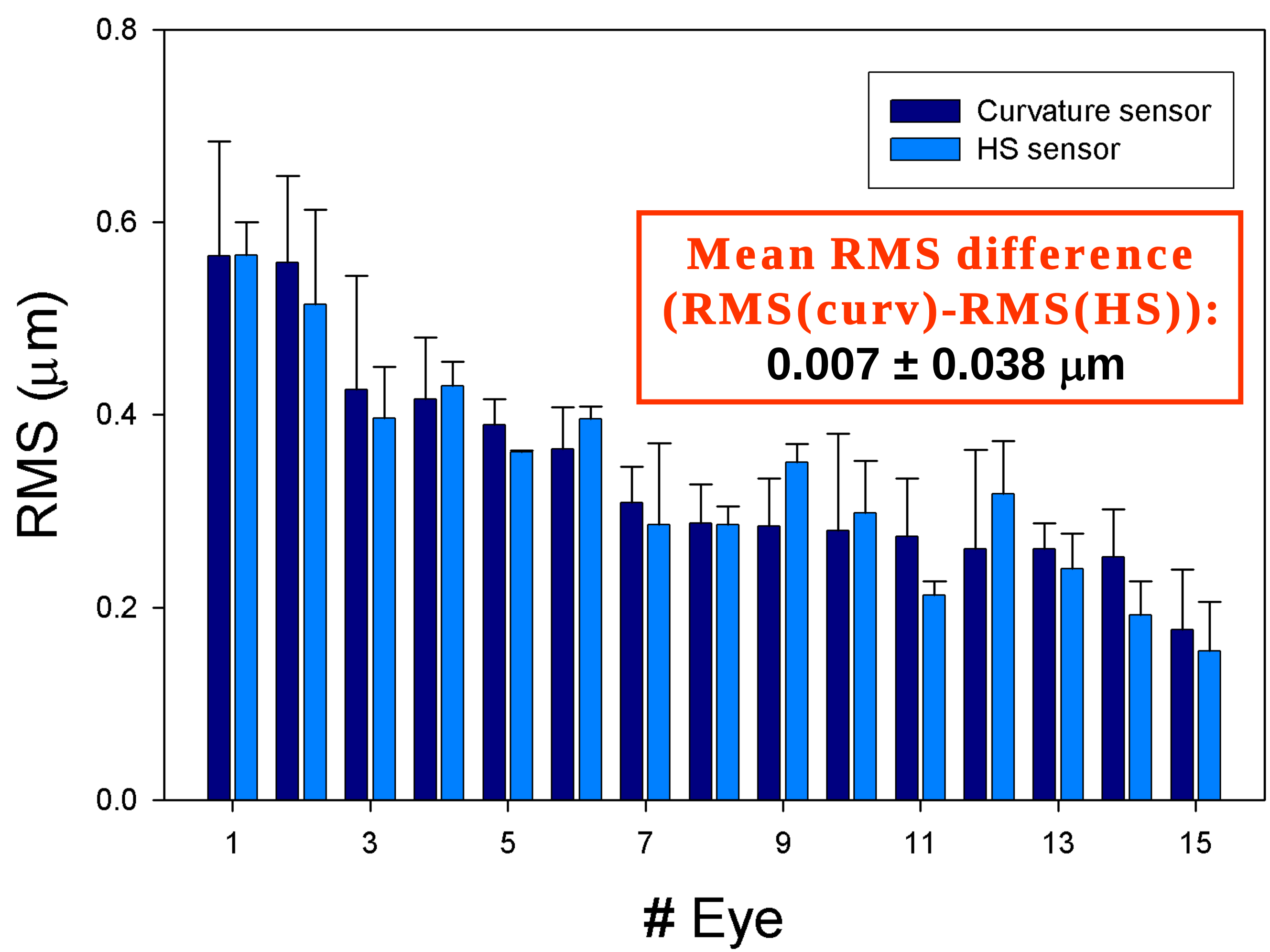
RMS 0.426 μm

Curvature sensing: a new method for ocular wave-front determination

Experimental results:

Real eye's measurements:

N	**15**
Mean age	**29.67 ± 5.83**
Mean refraction	**-1.27 ± 1.85**

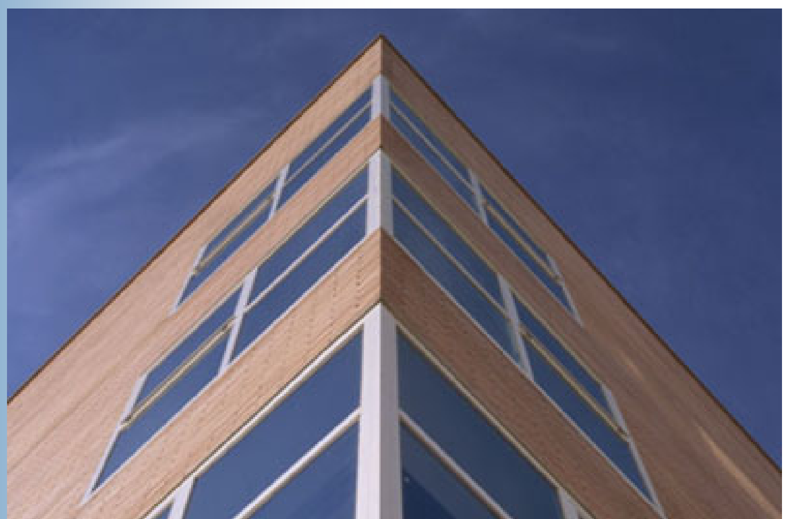


Conclusions:

- We have implemented a curvature based wave-front sensor for ocular aberration determination.
- The performance of the system has been tested by means of numerical simulations, setting important parameters affecting the sensor's operation.
- The wave-front retrieval algorithm has been reformed. The new features make it faster with an increase in accuracy.
- Experimental measurements for both artificial and real eyes show results comparable to conventional sensors.
- Further work is needed to show the full potential of this technique.

Thank you for your attention!

Centre de Desenvolupament de Sensors, Instrumentació i Sistemes
Departament d'Òptica i Optometria
UNIVERSITAT POLITÈCNICA DE CATALUNYA



CD6

TERRASSA

e-mail: diaz@oo.upc.edu