OPTICA adaptativa en Astronomía y Visión

Las Fronteras de la Física

Benasque, Julio 2004

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lo um

LABORATORIO DE OPTICA
UNIVERSIDAD DE MURCIA

ÓPTICA (Fotónica)

- Aplicación de la Física en (casi) todas las demas ciencias y la tecnología

- Proporciona las herramientas necesarias para entender fenómenos físicos en la frontera

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ÓPTICA (Fotónica)

- Optica ultra-rápida/ultra-intensa
- Experimentos en óptica cuántica
- Imágenes bio
- Micromanipulación
- Cristales fotónicos
- y mucho más…
- Optica adaptativa

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¿Que es la Óptica Adaptativa?

¡Tecnología para corregir las aberraciones ópticas y obtener "mejores" imágenes!

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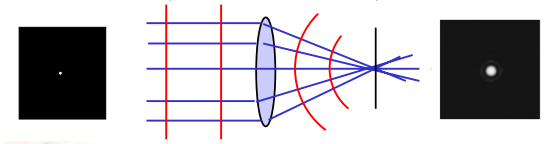
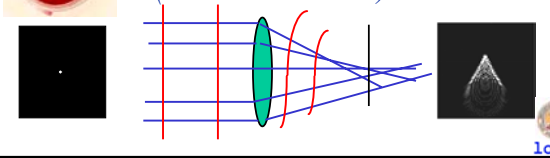
Sistema óptico "perfecto"
(sin aberraciones)



Sistema óptico REAL
(con aberraciones)



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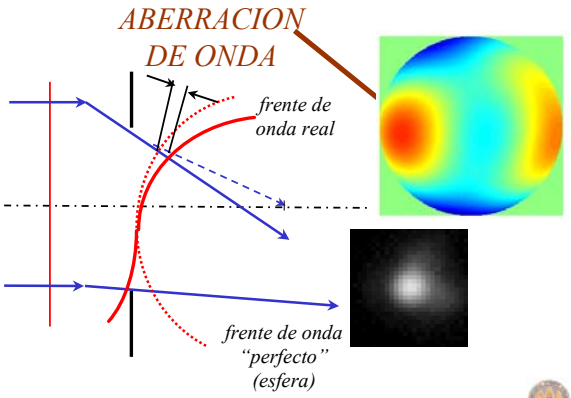
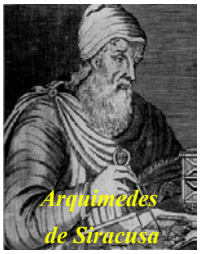
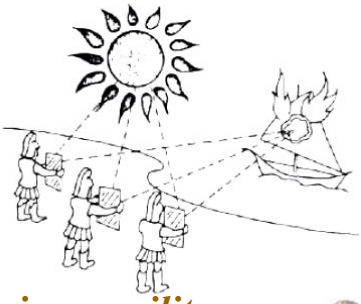


Óptica Adaptativa





De las aplicaciones militares...

Óptica Adaptativa

a astronómicas...

Óptica Adaptativa

…y a las aplicaciones en el ojo.

La resolución de los grandes telescopios está limitada por la atmósfera...

límite de difracción en un telescopio de 10 m (~λ/D):

~ 0.01 arcsec

en el "mejor cielo posible":

~ 0.5 arcsec

Posibles soluciones:

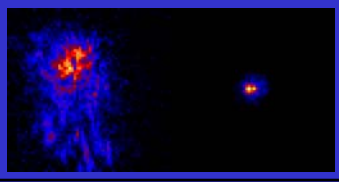
Telescopios espaciales → *Óptica adaptativa*

How does adaptive optics help?

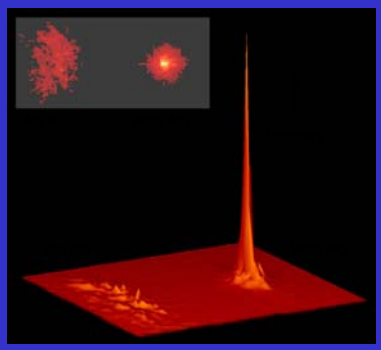
Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



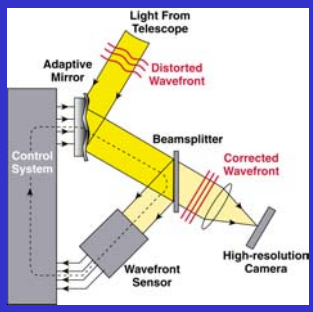
Adaptive optics increases peak intensity of a point source



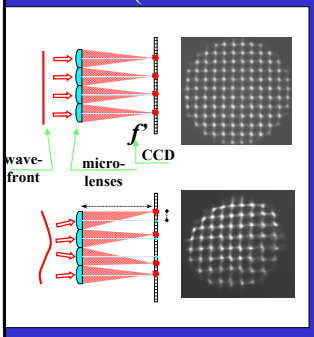
Lick Observatory

Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle



How to measure turbulent distortions (one method among many)

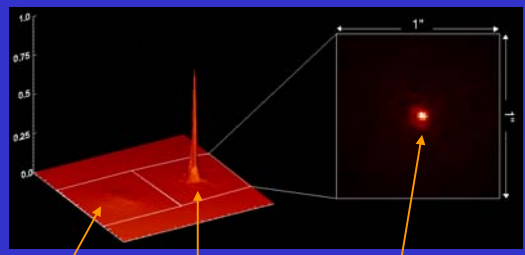


Theoretical principle:
The displacements of the spots produced by a microlens array are proportional to the wave-front local slopes (derivative)

WA estimation:
Fitting the WA derivative to obtain the coefficients of an expansion (Zernike or Taylor polynomials)

Hartmann-Shack wavefront sensor

Keck AO system performance on bright stars is spectacular!



Without AO
FWHM 0.34 arc sec
Strehl = 0.6%

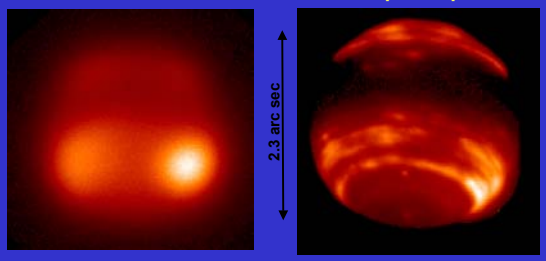
With AO

FWHM 0.039 arc sec
Strehl = 34%

Neptune in infra-red light (1.65 microns)

Without adaptive optics

With Keck adaptive optics

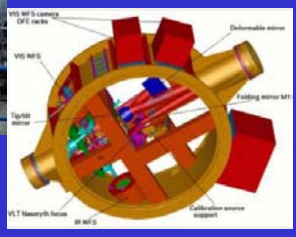


May 24, 1999

June 27, 1999

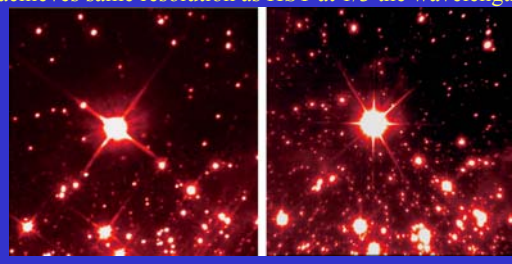
European Southern Observatory: 4 8-m Telescopes in Chile

NAOS - the AO system for the Very Large Telescope in Chile



VLT NAOS AO first light

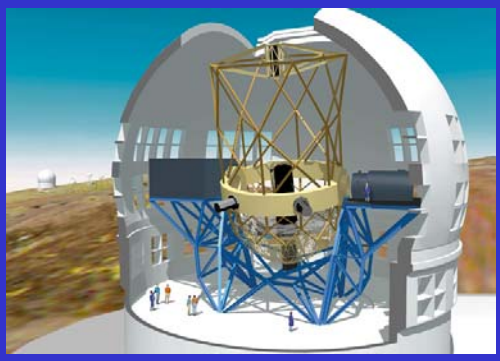
Cluster NGC 3603: IR AO on 8m ground-based telescope achieves same resolution as HST at 1/3 the wavelength



Hubble Space Telescope WFPC2, λ = 800 nm

NAOS AO on VLT λ = 2.3 microns

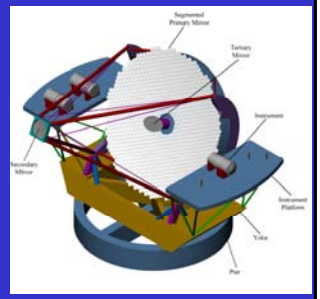
Gran Telescopio Canarias



Telescopios "gigantes" (>30 metros)

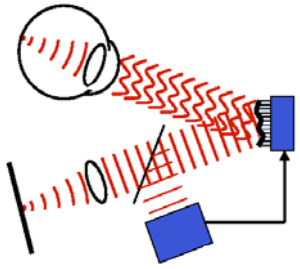
Mayores telescopios actuales (10 m)
λ/D ~ 0.02 arcsec (1 μm) con OA

Telescopios en planificación (30-100 m)
λ/D ~ 0.007 arcsec (1 μm) (30 m) con OA



California Extremely Large Telescope (CELT) 30 m

Óptica Adaptativa en el ojo



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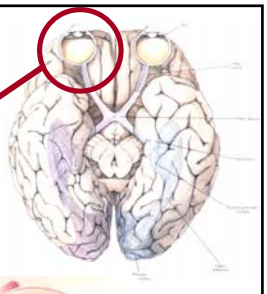
1994-2004: 10 years of research

http://lo.um.es

Sistema visual

Óptica del ojo



escena

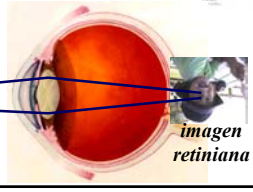
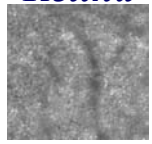
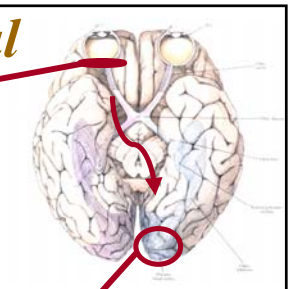


imagen retiniana

Sistema visual

Retina





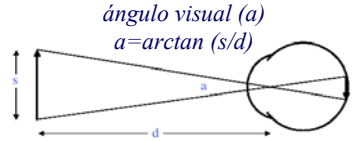
Cortex

Resolución del sistema visual (Agudeza visual):

inverso del ángulo subtendido por el detalle más pequeño discernido

luna ~ 30′

E



trazo de letra ~ 1′

Agudeza visual

lince ~ 0.1

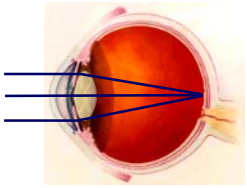
hombre ~ 1

águila ~ 2.5

-

+

Óptica del ojo:



Óptica del ojo:
no es perfecta:

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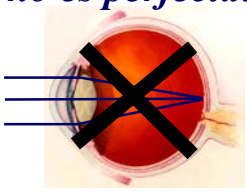
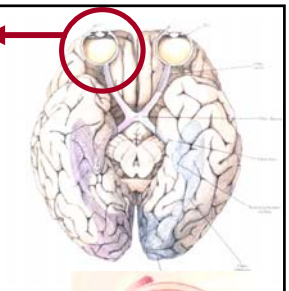
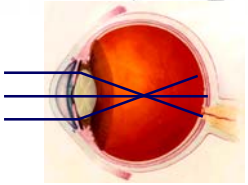
no es perfecta:





Además de desenfoque y astigmatismo…



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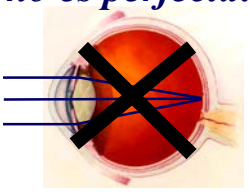

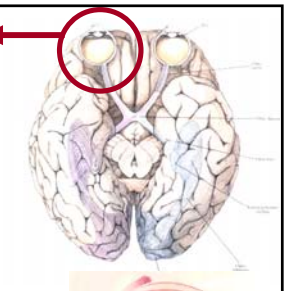

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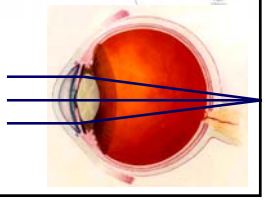

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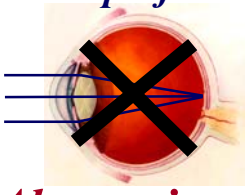
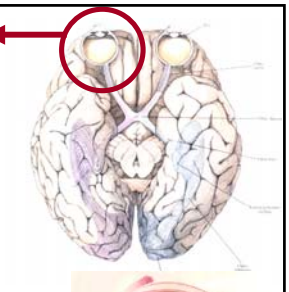
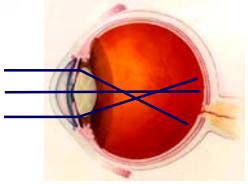




Aberraciones: límite físico a la visión!



Aberraciones del ojo

(un poco de historia)

1800

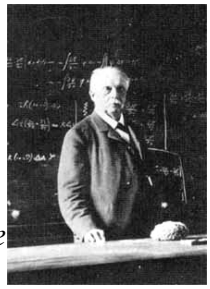
1900

1950

1990

Helmholtz

"...si un fabricante tratara de venderme un aparato de óptica con una calidad tan mala como la del ojo, lo rechazaría directamente y le reprendería por su poco cuidado"



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Aberraciones del ojo

(un poco de historia)

1800 — **Helmholtz**

1900 — **Gullstrand (1911)**

1950

1990

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Aberraciones del ojo

(un poco de historia)

1800 — **Helmholtz**

1900 — **Gullstrand (1911)**

1950 — Ames and Proctor (1921); Arnulf et al.; Ivanoff; Koomen et al. (40's) } *medida de aberraciones*

Smirnov (1961) } *aberración de onda*

1990 — *Óptica Adaptativa!*

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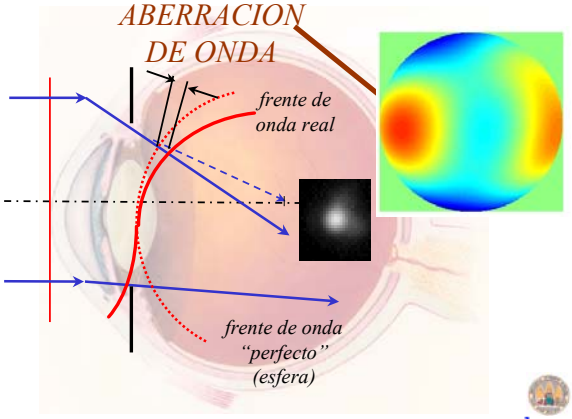
ABERRACION DE ONDA



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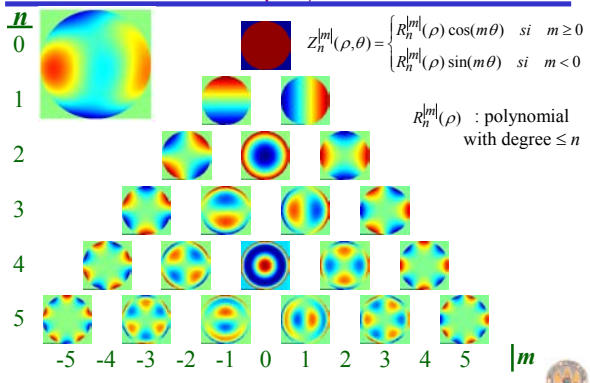
Zernike polynomials



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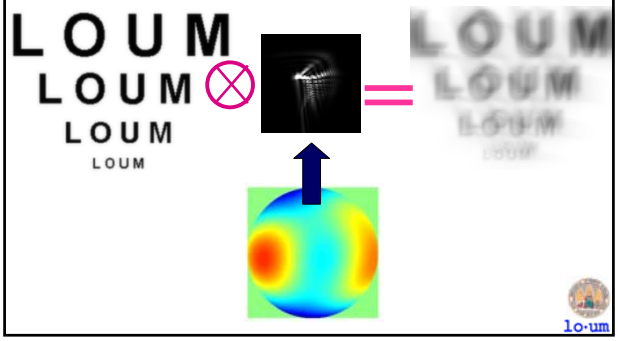
De las aberraciones a las imágenes retinianas...



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How to measure ocular aberrations?

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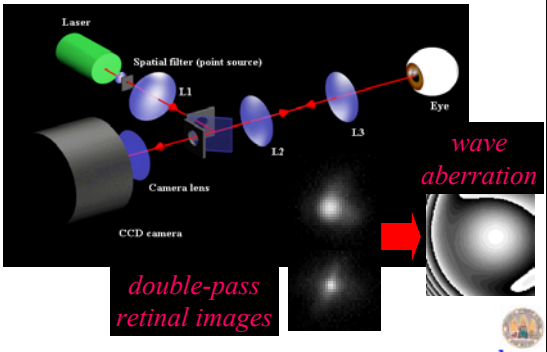
Aberrations from Double-Pass images

(*Santamaría et al., J.Opt.Soc.Am.A.,1987; Artal, et al. J.Opt.Soc.Am.A.,1988*)



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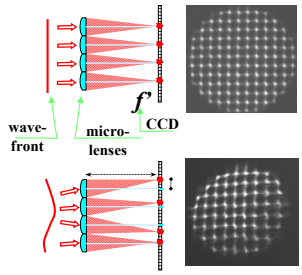
Hartmann-Shack (H-S) wave-front sensor



Theoretical principle:
The displacements of the spots produced by a microlens array are proportional to the wave-front local slopes (derivative)

WA estimation:
Fitting the WA derivative to obtain the coefficients of an expansion (Zernike or Taylor polynomials)

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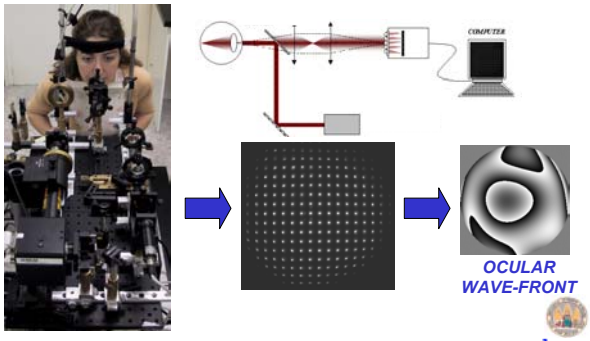
University of Murcia-high dynamic range Hartmann-Shack wave-front sensor



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How are the aberrations in normal eyes?

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It depends on different factors...

- *Intersubject variability*
- *Pupil size*
- *Accommodation*
- *Eye torsions*
- *Retinal eccentricity*
- *Age...*

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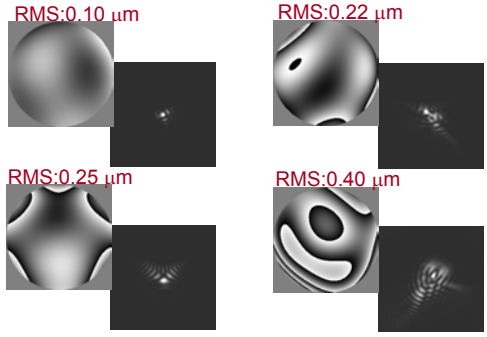
Inter-subject variability

(*Castejón-Mochón et al., Vision Res., 2002*)



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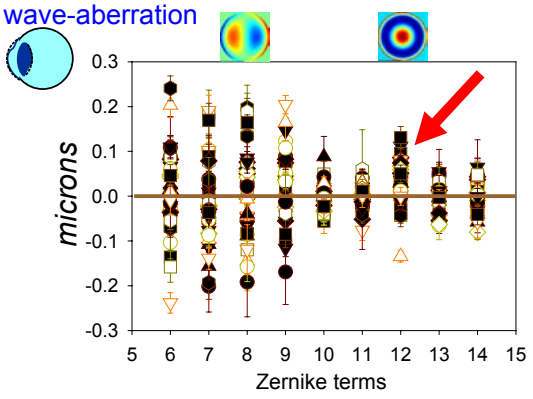
OCULAR
wave-aberration



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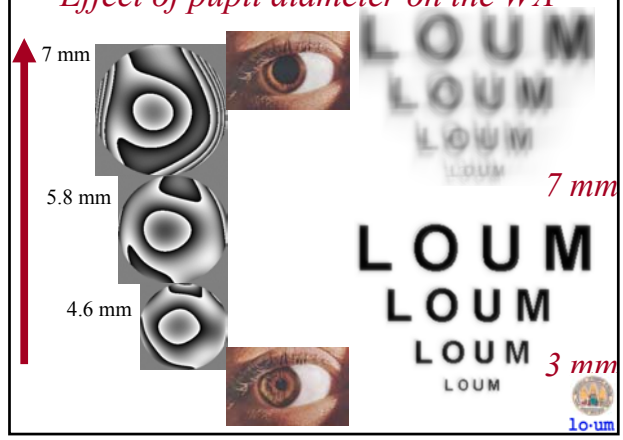
Effect of pupil diameter on the WA



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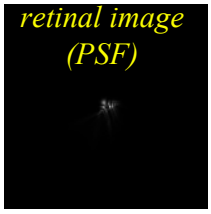
Aberrations change with accommodation

subject SM (26 years old)

wave-aberration (-defocus) 5.5 mm pupil

retinal image (PSF)



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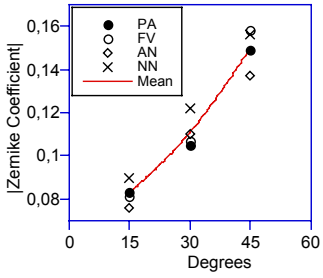
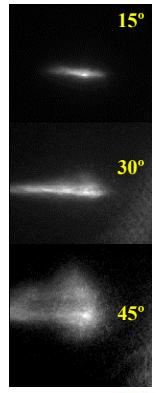
Aberrations increases with retinal eccentricity

(*Guirao and Artal, Vision Res.,1999*)





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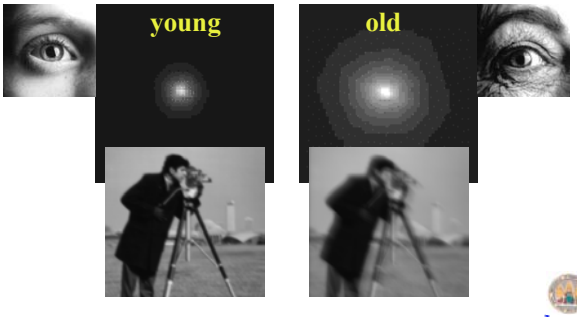
Aberrations increase with age

(*Artal et al., JOSAA, 1993; Guirao, González, Redondo, Geraghty, Norrby & Artal, IOVS, 1999*)



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Aberrations in (some) pathological eyes

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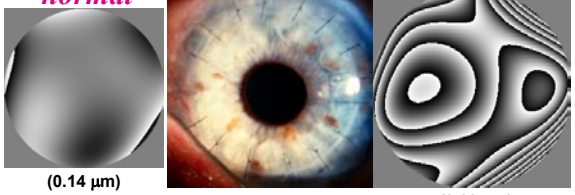
Aberrations in normal versus pathological eyes

Penetrating Keratoplasty (PK)

normal

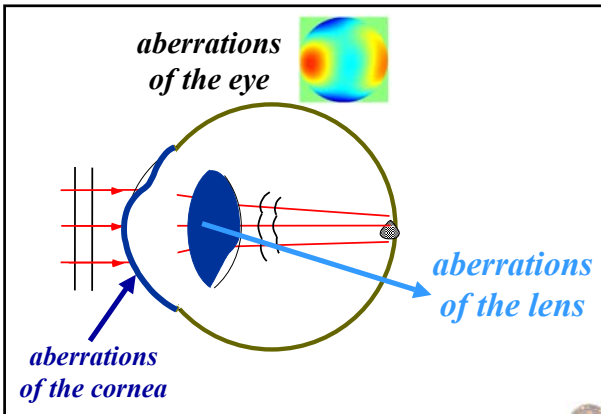


(0.14 µm)

(0.89 µm)

Location (sources) of ocular aberrations

(Artal, Guirao, Berrio & Williams, Journal of Vision, 1, 2001)



How to estimate the lens aberrations in vivo?

lens = eye - cornea

(Artal and Guirao, Opt.Lett., 1998; Artal et al., JOV,2001)

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lens = eye - cornea

(Artal and Guirao, Opt.Lett., 1998; Artal et al., JOV,2001)

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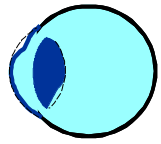

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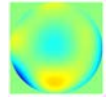
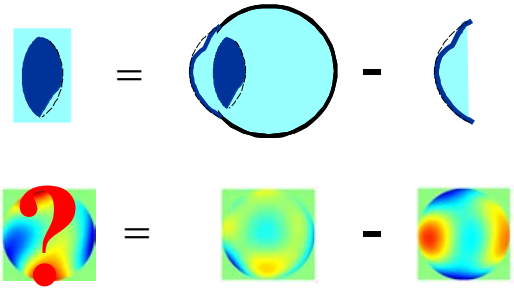


lens = *eye - cornea*

(Artal and Guirao, Opt.Lett., 1998; Artal et al., JOV,2001)

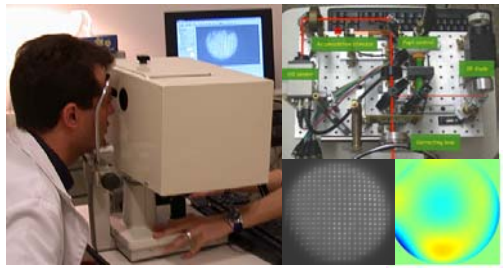


Estimating ocular aberrations

(Prieto, Vargas, Goelz & Artal, J.Opt.Soc.Am.A.,2000)

Hartmann-Shack wave-front sensor

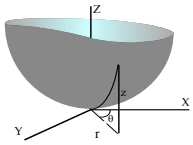
(University of Murcia-high dynamic & real-time sensor)



Estimating corneal aberrations

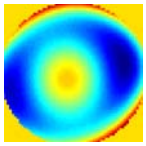
(Guirao & Artal, J.Opt.Soc.Am.A., 17, 2000)

corneal elevations (z) at a sample of points over the pupil



(c_n^m)

...fitted to a Zernike polynomials expansion

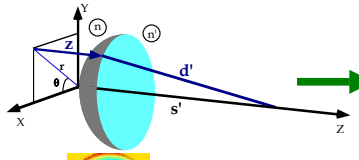


$$z(r,\theta) = \sum_{n=0}^{L} \sum_{m=-n}^{n} a_n^m Z_n^m(r,\theta)$$

Estimating corneal aberrations

(Guirao & Artal, J.Opt.Soc.Am.A., 17, 2000)

$W = n\,z + n'\,d' - n'\,s'$



$z(r,\theta)$

(c_n^m)

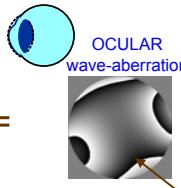
CORNEAL wave aberration

$$W(r,\theta) = \sum_{n=0}^{L} \sum_{m=-n}^{n} c_n^m Z_n^m(r,\theta)$$

$$c'^m_n = c''^m_n - c^m_n \qquad c''^m_n - c^m_n$$

INTERNAL wave-aberration

=



OCULAR wave-aberration

−

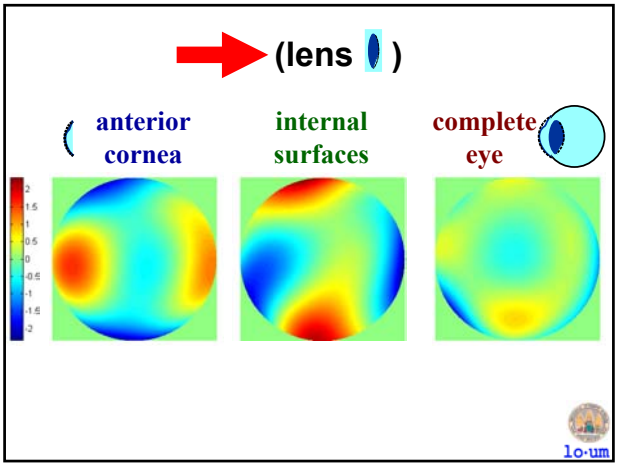
CORNEAL wave-aberration

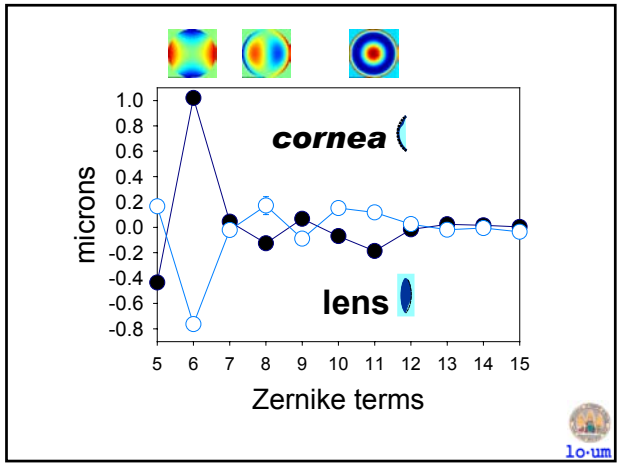
both centered with respect to the geometric center of the pupil

(lens)!!

The lens (partially) compensates for the corneal aberrations in young subjects

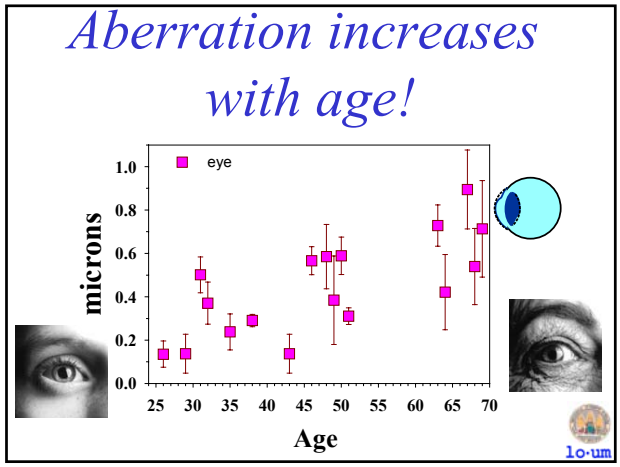
(Artal, Guirao, Berrio & Williams, Journal of Vision, 1, 2001)

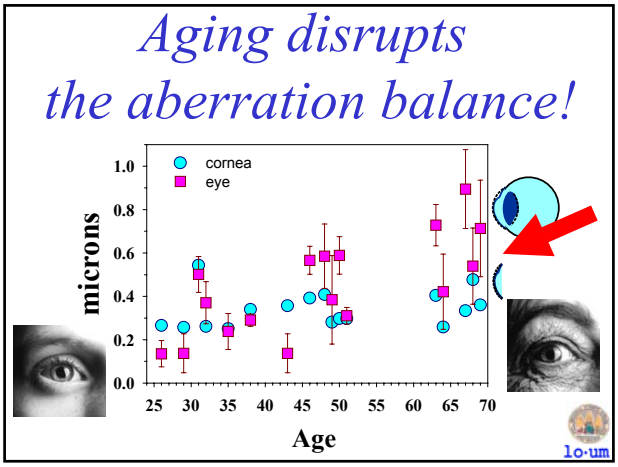


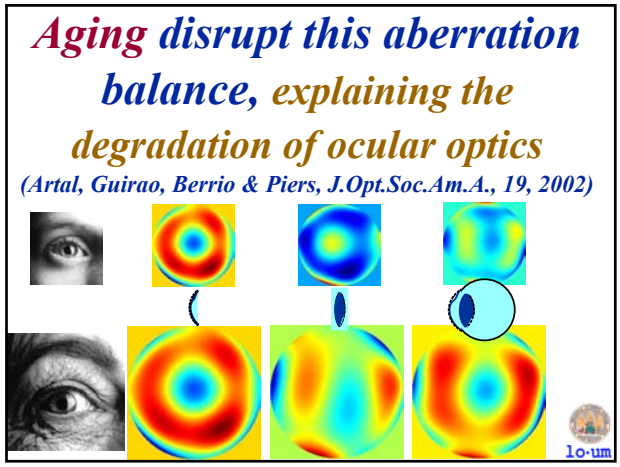


Aberrations of the lens in older subjects

(Artal, Guirao, Berrio & Piers, J.Opt.Soc.Am.A., 19, 137, 2002)







Corrección de las aberraciones del ojo *(algo más de historia...)*

sXIII desenfoque

1800

1960

1990

200?

Corrección de las aberraciones del ojo *(algo más de historia...)*

sXIII desenfoque

1800 astigmatismo (Young)

1960

1990

200?

Corrección de las aberraciones del ojo *(algo más de historia...)*

sXIII desenfoque

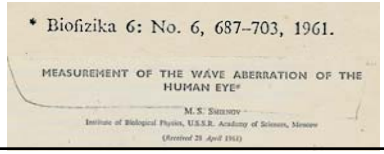
1800 astigmatismo (Young)

aberraciones de alto orden

1960 propuesta (Smirnov)

1990

200?



Biofizika 6: No. 6, 687–703, 1961.

MEASUREMENT OF THE WAVE ABERRATION OF THE HUMAN EYE*

M. S. Smirnov

Institute of Biological Physics, U.S.S.R. Academy of Sciences, Moscow

(Received 28 April 1961)

Corrección de las aberraciones del ojo *(algo más de historia...)*

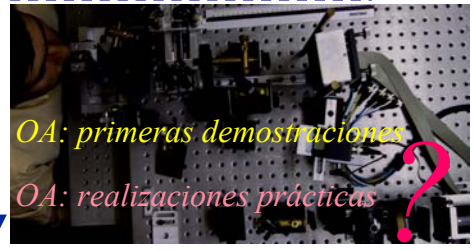
sXIII desenfoque

1800 astigmatismo (Young)

1960

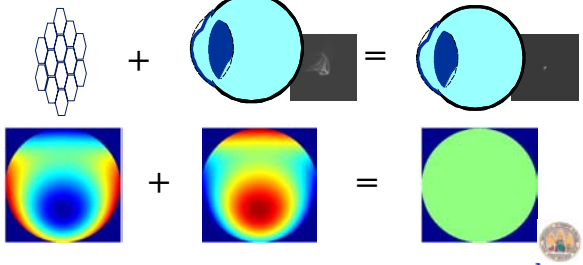
1990 OA: primeras demostraciones

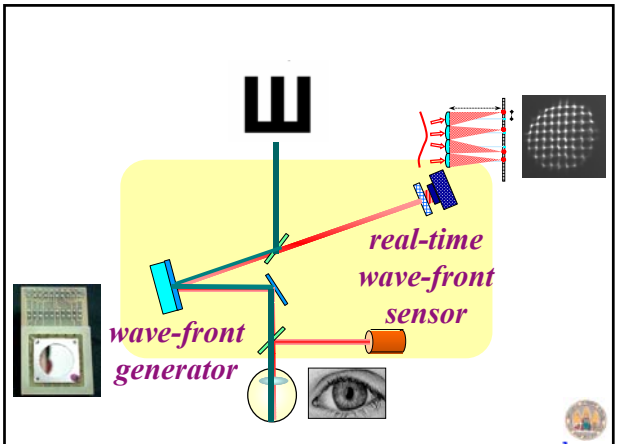
200? OA: realizaciones prácticas ?

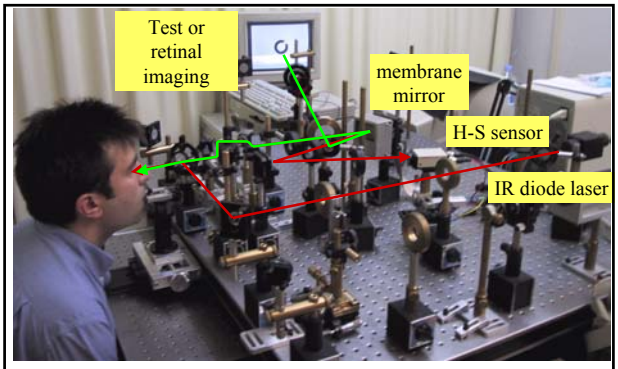


Óptica Adaptativa *en el ojo*

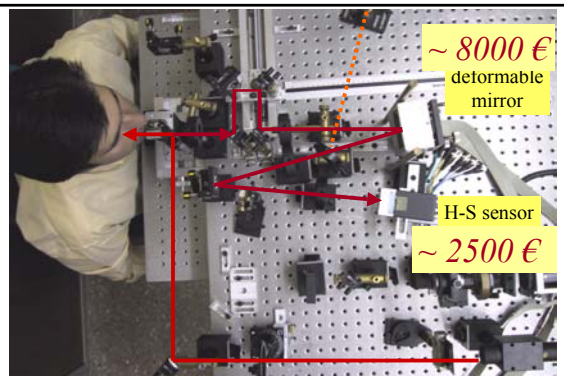
corrector + *Ojo aberrado* = *Ojo sin aberraciones*





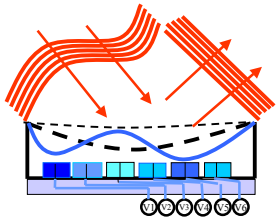


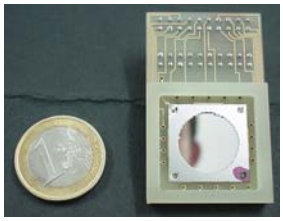
LO·UM closed-loop real-time (25 Hz) AO for the human eye *(Fernández, Iglesias & Artal, Optics Letters, 2001)*



Low-cost key components!

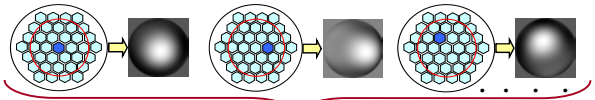
Corrector device: 37 channels membrane deformable mirror (MDM) from OKO





Static correction in an artificial eye *(Zhu et al., App. Opt.,1999)*
Closed-loop AO in artificial turbulence *(Patterson et al., Opt.Exp.,2000)*
Closed-loop astronomical AO *(Dayton et al. Opt.Comm,2000)*

Mirror control procedure



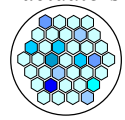
***I**nfluence **F**unctions **M**atrix (IFM)*

(SVD)

$[IFM]^{-1}$ x

desired mirror surface

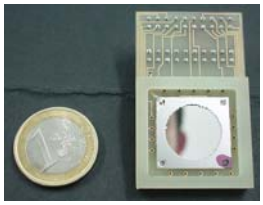
=

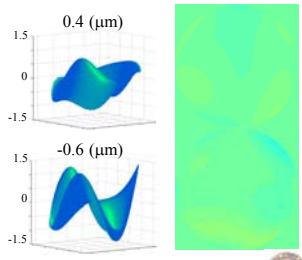


voltages of actuators

Wave-front generator

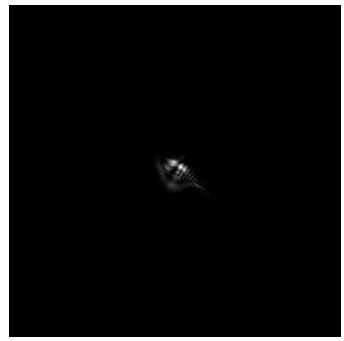
37 channels membrane deformable mirror from OKO (Holland)



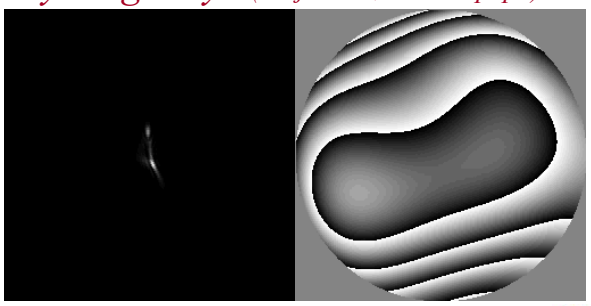


Closed-loop correction in subject PA

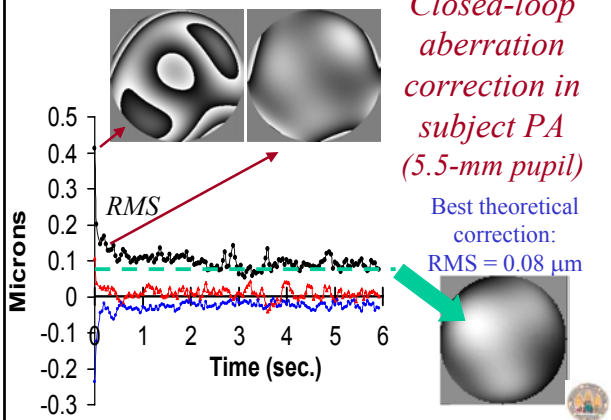
AO
OFF-ON



Closed-loop correction in a younger eye *(subject ES; 4.3 mm pupil)*

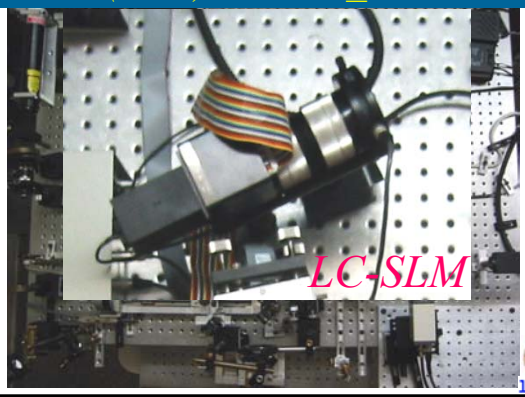


Closed-loop aberration correction in subject PA (5.5-mm pupil)

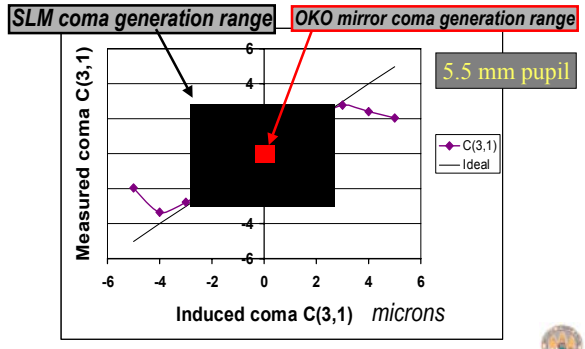


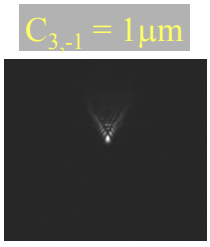
Best theoretical correction: RMS = 0.08 µm

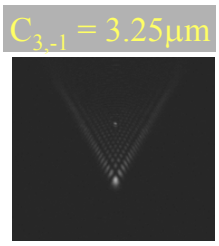
(SLM) LO·UM_AO



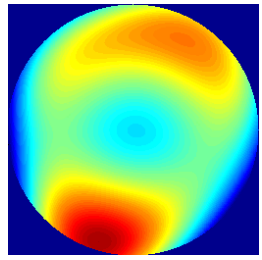
ABERRATIONS GENERATION







AO OFF-ON



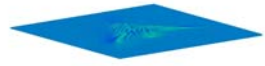
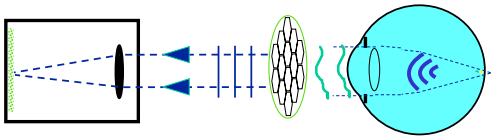
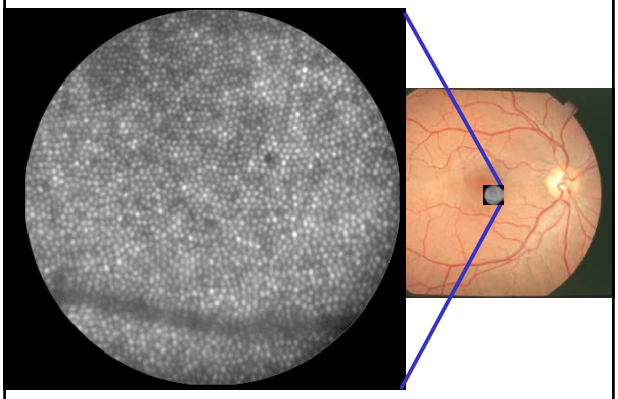


imagen retiniana

Aplicaciones de la Óptica Adaptativa en en ojo:

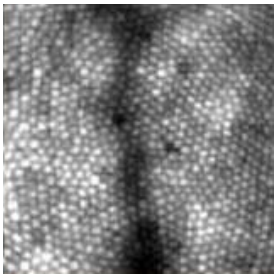
- *mejorar la visión*
- ***imágenes de la retina***
- *simular la visión*

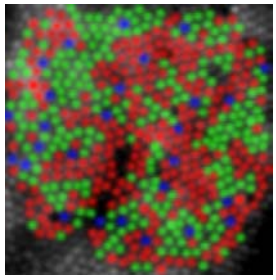




(Cortesía de David Williams)

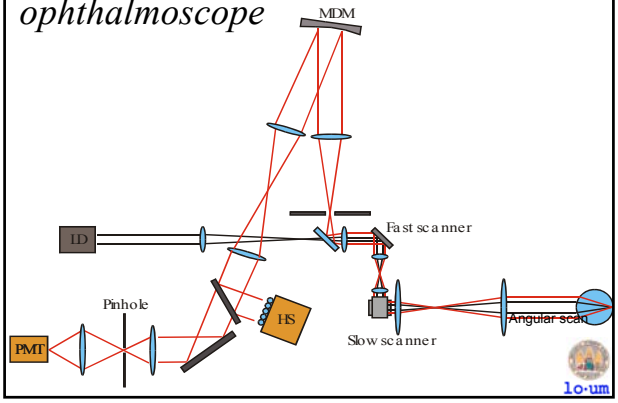
A. Roorda and D.R. Williams, Nature, 397, 520-522, 1999



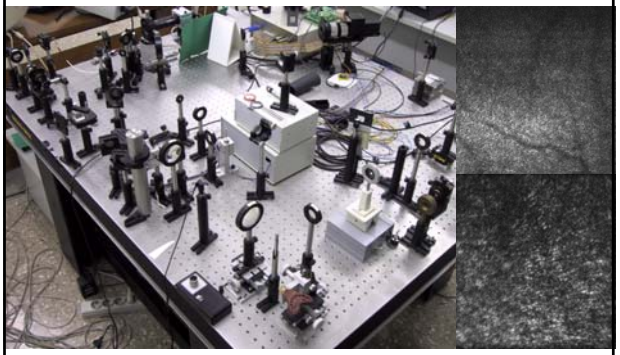


(Courtesy Austin Roorda & David Williams)

LO·UM_AO_Scanning laser ophthalmoscope



LO·UM AO-SLO



Results from University of Houston AO_SLO

(Courtesy Austin Roorda)

MM OS

Photoreceptors
4.5 deg superior to fovea

AOSLO Houston 03/01/2002

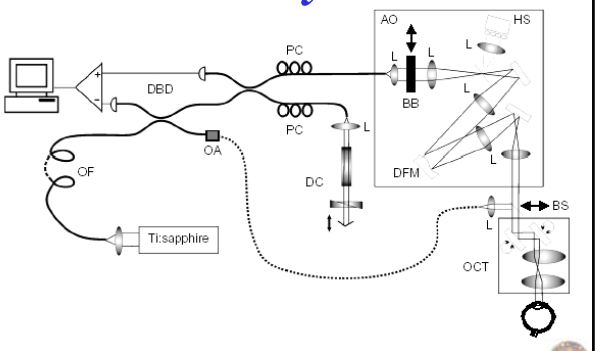
Results from University of Houston AO_SLO

(Courtesy Austin Roorda)

Photoreceptors and Blood Flow

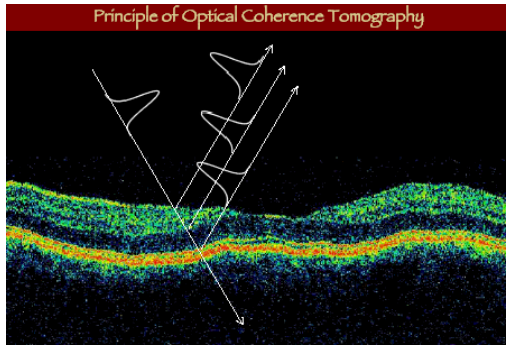
AR OS 02/05/02

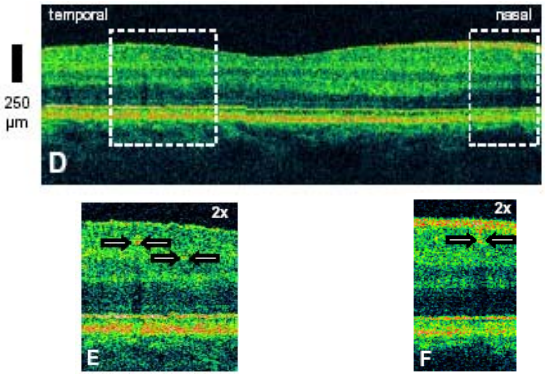
AO-UH OCT system



LO·UM-University of Vienna (2004)

lo·um





LO·UM-University of Vienna (2004)

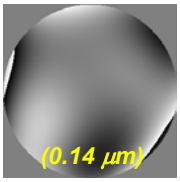
lo·um

Aplicaciones de la Óptica Adaptativa en en ojo:

- ***mejorar la visión***
- ***imágenes de la retina***
- ***simular la visión***

lo·um

El beneficio visual de la corrección es quizás modesto en ojos normales...



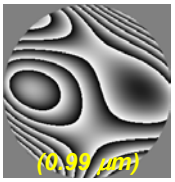
Imágenes retinianas (en ojos normales)

SIN CORRECCION

CON CORRECCION

… pero puede ser muy importante en ojos con altos niveles de aberración

queratocono



… pero puede ser muy importante en ojos con altos niveles de aberración

tras transplante de cornea

Imágenes retinianas (en ojo con cornea transplantada)*

SIN CORRECCION

CON CORRECCION (parcial)

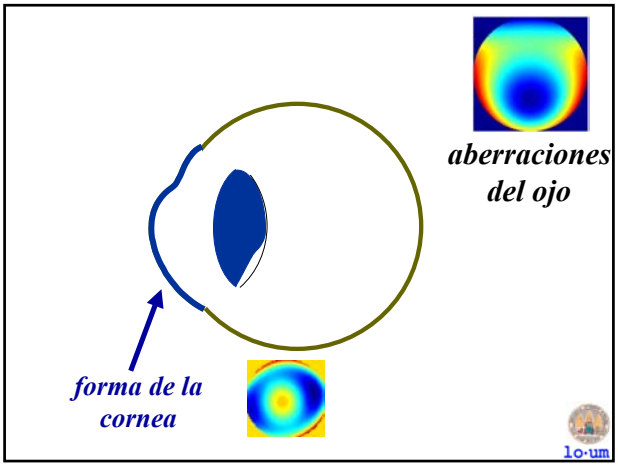
1º

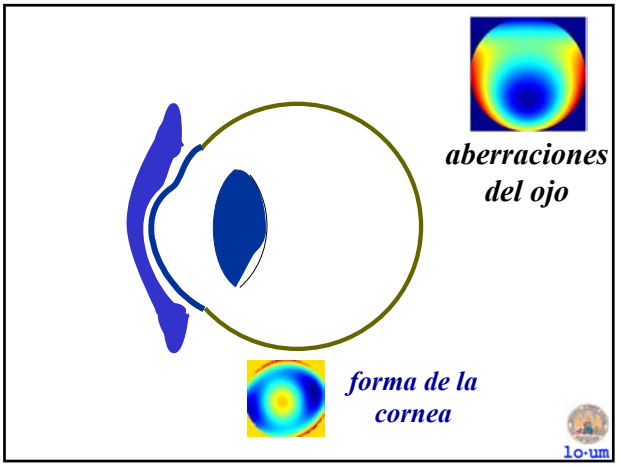
¿Es posible la corrección "práctica" de aberraciones?

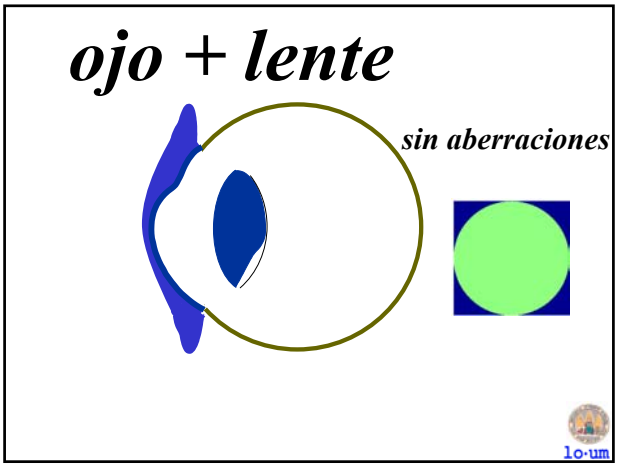
¿Con... lentes de contacto?

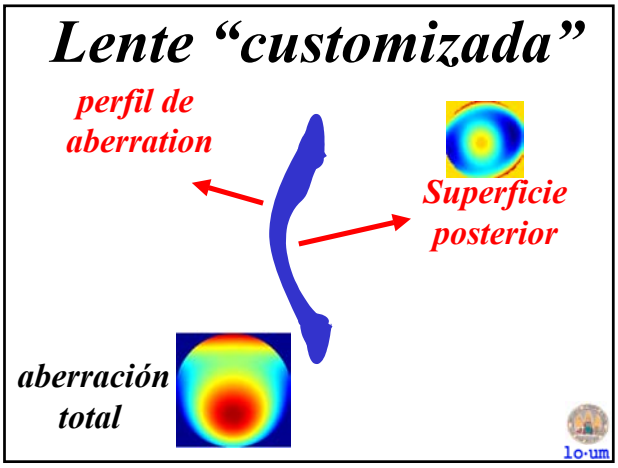
¿Con... lentes intraoculares?

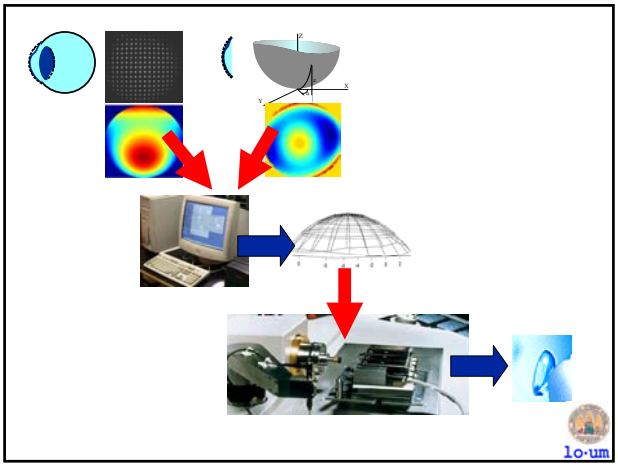
¿Con... cirugía refractiva?









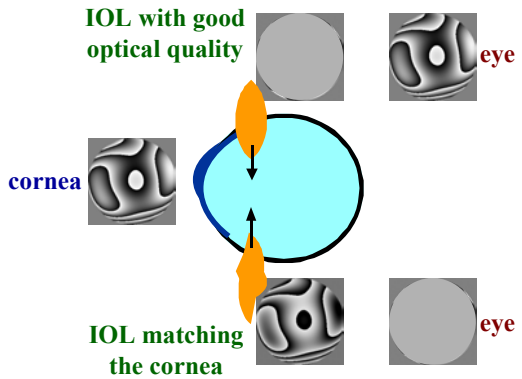


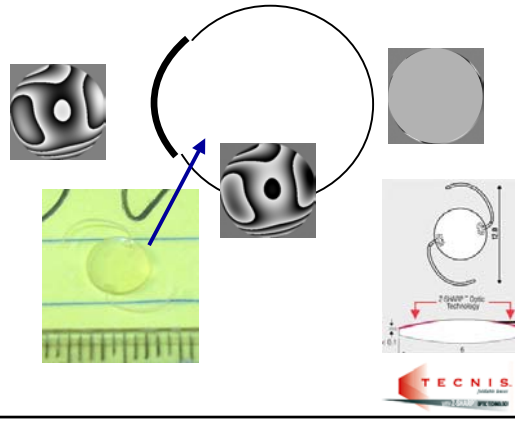
¿Es posible la corrección “práctica” de aberraciones?

¿Con... lentes de contacto?

¿Con... lentes intraoculares?

¿Con... cirugía refractiva?



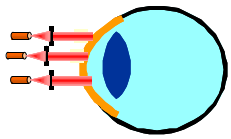


¿Es posible la corrección "práctica" de aberraciones?

¿Con... lentes de contacto?

¿Con... lentes intraoculares?

¿Con... cirugía refractiva?



?

control del perfil de ablation

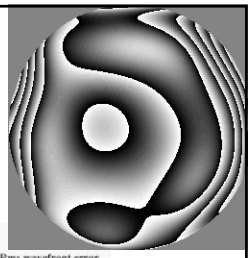
Limits of static corrections!

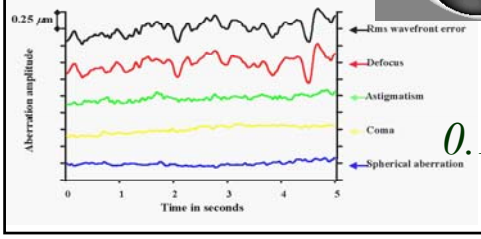
Ocular aberrations are dynamic!!

Even if perfect STATIC corrections were possible... they will be limited by...

Aberrations change over time

(Hofer, Artal, Singer, Aragón & Williams, J.Opt.Soc.Am.A. 2001)





2 Hz

0.12 D !!

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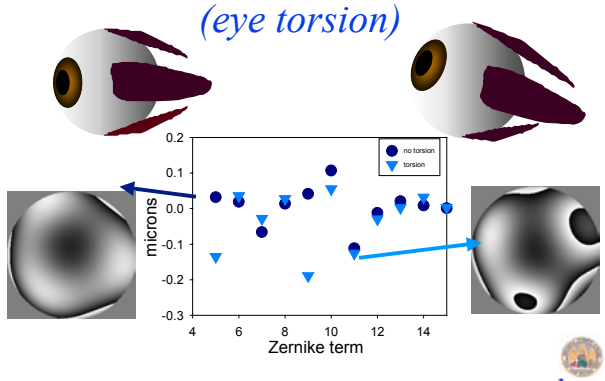
Aberrations change with gaze *(eye torsion)*



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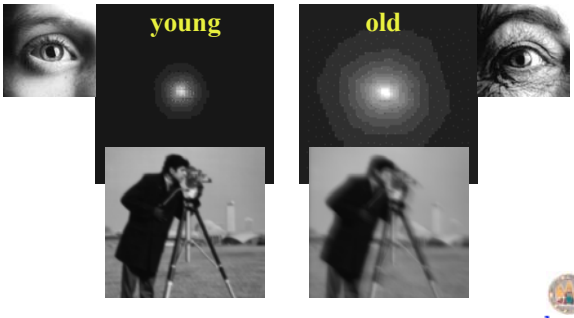
Aberrations increase with age

(Artal et al., JOSAA, 1993; Guirao, González, Redondo, Geraghty, Norrby & Artal, IOVS, 1999)



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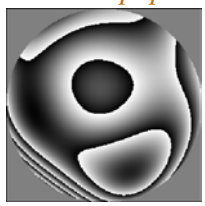
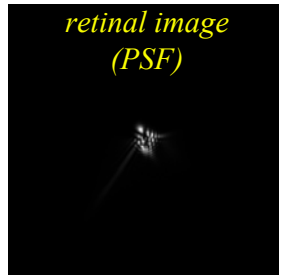
Aberrations change with accommodation

subject SM (26 years old)

wave-aberration (-defocus) 5.5 mm pupil



retinal image (PSF)



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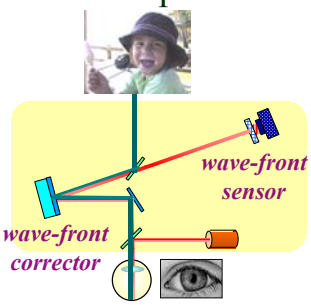
Real-time aberration correction (Adaptive optics)

- electro-optical AO spectacles?



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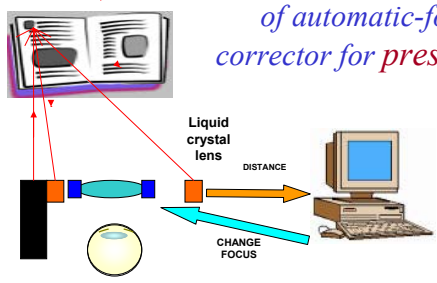
Practical implementations???

- Automatic correction of defocus

Example of LO·UM prototype of automatic-focus corrector for presbyopia



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Limits of adaptive corrections!!

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additional limits to vision...

Even if perfect ADAPTIVE corrections were possible... they will be limited by...

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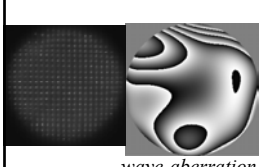
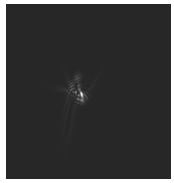
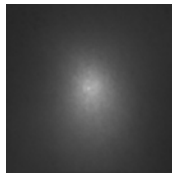
Intraocular scattering



wave-aberration (5 mm)



from aberrations (HS)



from double-pass (OQAS)

pre-cataract eye!!!

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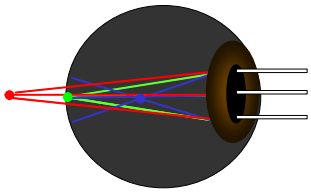
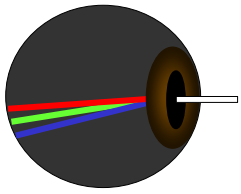
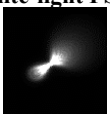
Chromatic aberration





monochromatic PSF

white-light PSF



white-light PSF

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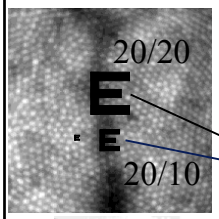
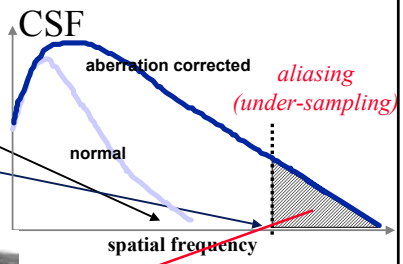
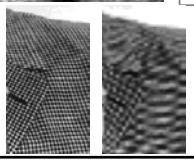
Retinal and neural limits







60 c/deg = frec. Nyquist

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Even if possible... would you really need an ideal "perfect" correction?

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WARNING

Visual performance may take advantage of aberrations!

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Some possible beneficial effects for vision of aberrations:

- *Driving accommodation...*
- *Avoiding aliasing artifacts*
- *Color vision may need aberrations...*
- *The visual system may be adapted to the own eye's aberration pattern...*

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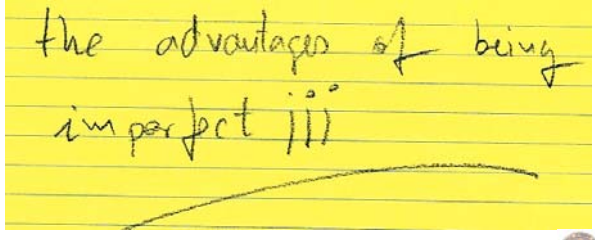
...good VISION may require a residual normal level of ocular aberrations.



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Aplicaciones de la Óptica Adaptativa en en ojo:

- mejorar la visión

- imágenes de la retina

- simular la visión

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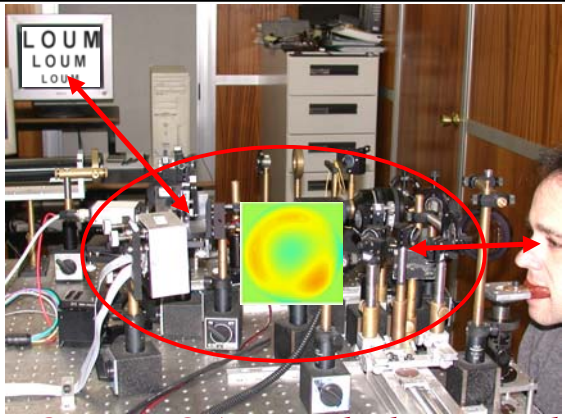

LO·UM OA simulador visual

SIMULADOR VISUAL de Óptica Adatativa

Diseño/testeo interactivo de nuevos sistemas en Óptica Oftálmica.



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SIMULADOR VISUAL de Óptica Adatativa

Predecir/medir la visión

E
H N
D F N
P T X Z
U Z D T F
D F N P T H

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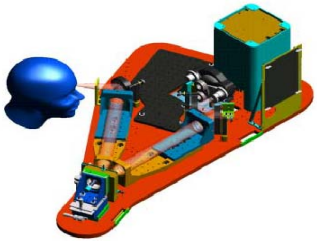
SIMULADOR VISUAL de Óptica Adatativa

Predecir/medir la visión



E
H N
D F N
P T X Z
U Z D T F
D F N P T H

OA-forópteros del siglo XXI

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¿Cual es el futuro de la Óptica Adaptativa en aplicaciones oftálmicas?

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- ***Nuevos oftalmoscopios de alta resolución...***
- ***Detección precoz de enfermedades de la retina***
- ***Micro-cirugía de alta precisión***
- ***Seguimiento de nuevas terapias***

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- ***Mejora de la cirugía refractiva...***
- ***Nuevas lentes de contacto, intraoculares…***
- ***"Gafas" opto-electrónicas para presbicia o casos especiales…***
- ***Forópteros de OA***

...y más!

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Thank you for
your attention,
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