Correction of NCPAs using a deformable lens in pyramid wavefront sensor-based AO systems: preliminary lab results

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Laboratorio Nazionale ADONI Ottica Adattiva

Multi-actuator Adaptive Lens (MAL)

- 18 piezo-electric actuators outside the clear aperture
- Clear aperture: 10mm
- Technology: PZT bimorph (Voltage range: -125V/+125V)

- Optical power: 1.4 D
- Transmission: visible-NIR >94% (no AR coating applied yet)
- Frequency up to 200 Hz
- Initial aberration: 0.1 waves rms corrected with about 10% voltage range
- Max stroke: 10 waves PtV (astigmatism)

Generates aberrations up to the 4th order

Aberration	Zernike order	PtV(μm)
Tilt	Z_{11}, Z_{1-1}	3
Defocus	Z_{20}	3.8
Astigmatism	Z_{22}, Z_{2-2}	7.7
Coma	Z_{31}, Z_{3-1}	2.2
Trefoil	Z_{33}, Z_{3-3}	2.9
Spherical Ab.	Z_{40}	0.5
Secondary Ast.	Z_{42}, Z_{4-2}	0.75
Quadrifoil	Z_{44}	1.2

- MAL electronic controller is connected to the laptop by means of USB and is very compact and lightweight

For more details on the MAL:
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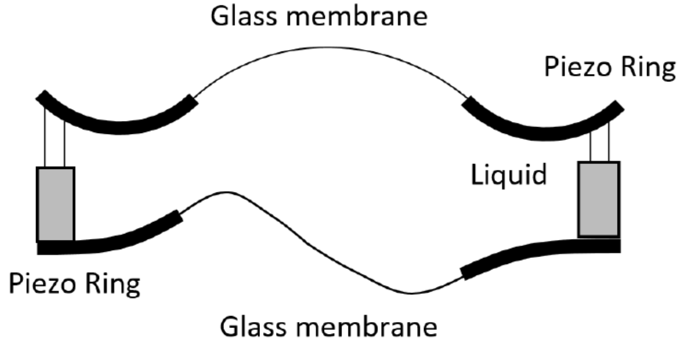
Adaptive lens mounted on a camera objective

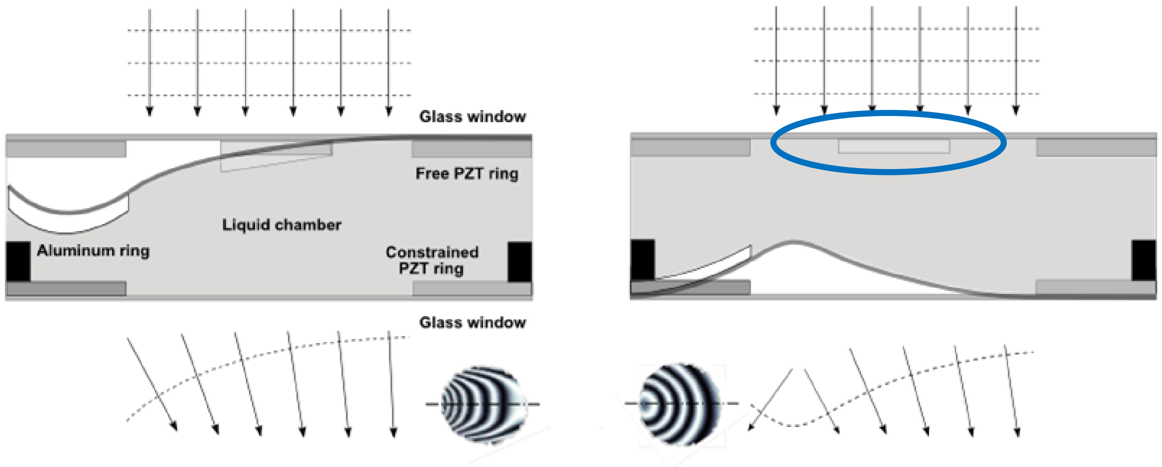
Multi-actuator Adaptive Lens (MAL)

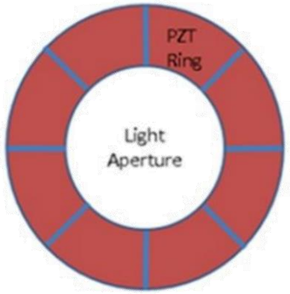
- N-BK7 optical windows (150 µm thick) filled with transparent liquid matching the refractive index of the glass

To produce aberrations up to the 4th order:

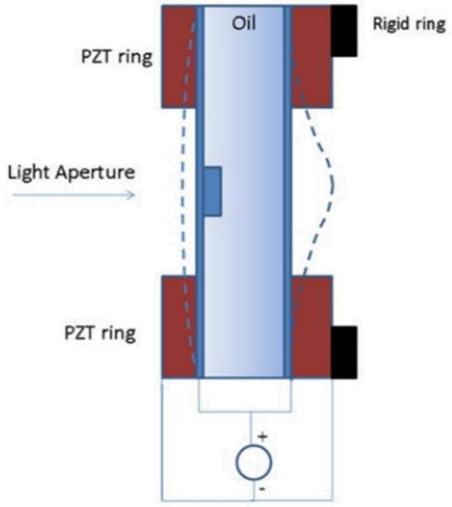
- Upper window: free to move (elastomer foam)
- Lower window: fixed at the border to a rigid aluminum ring
- Central part of the lens is stiffened with a glass disk with a refractive index matched to the liquid in order to generate the spherical aberration







8 actuator sectors

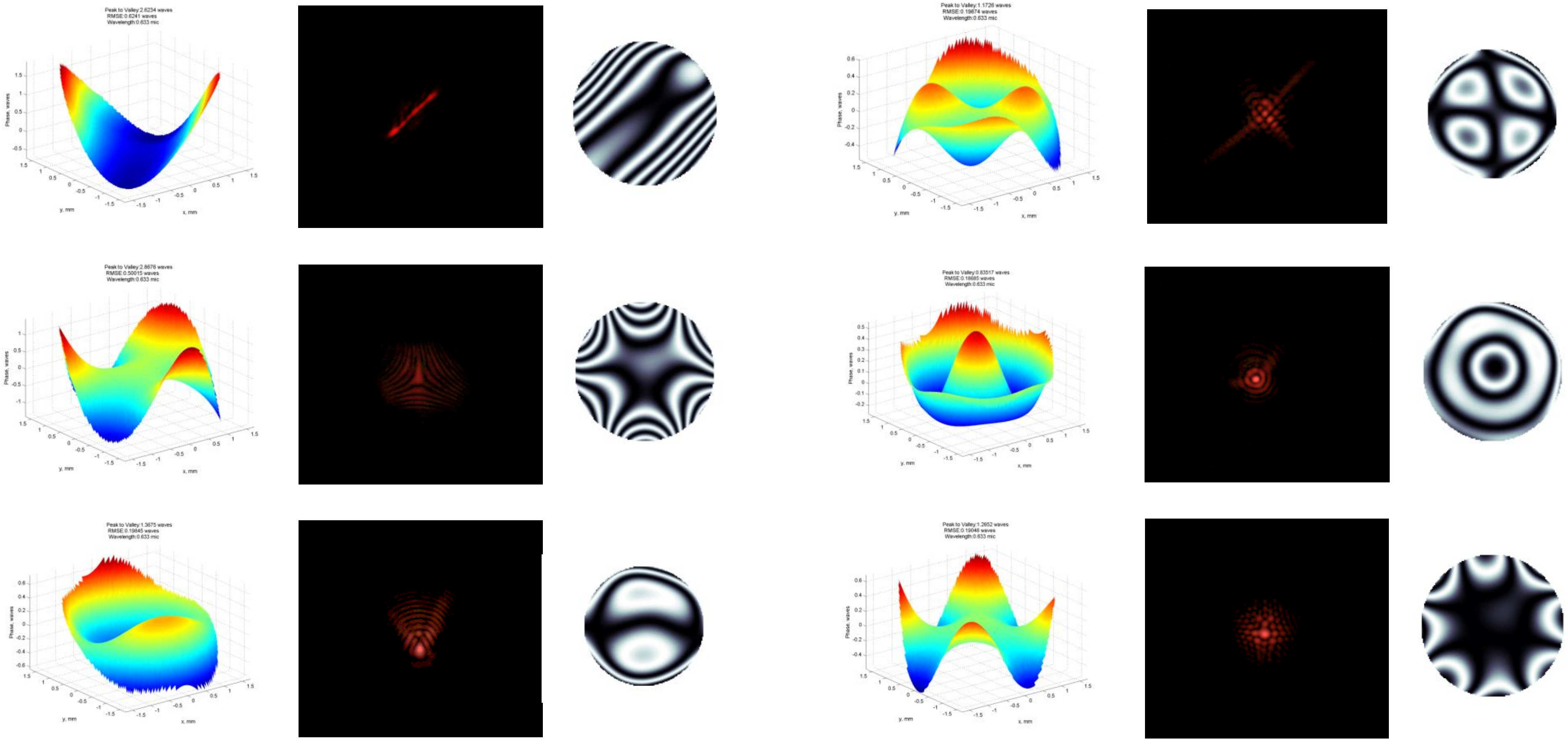


Multi-actuator Adaptive Lens (MAL)

Influence functions (tilt removed):

Top side actuators

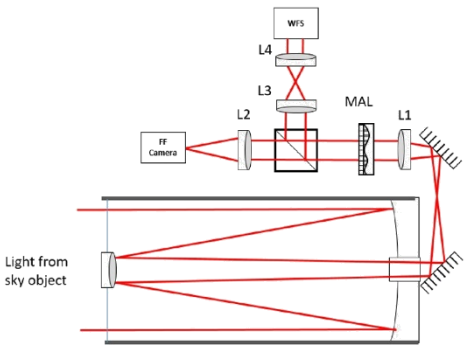
Bottom side actuators



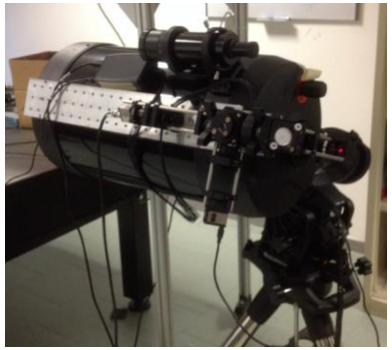
MAL applications

- It has all features to close a loop with a WFS

- In microscopy, it was used for aberrations corrections for *in vivo* ophthalmic imaging applications, after being characterised in an AO system with a SH-WFS
  Stefano Bonora et al, Opt. Express 23, 21931-21941(2015)



What about astronomical applications?!?



- At this stage they cannot be considered substitute of DMs

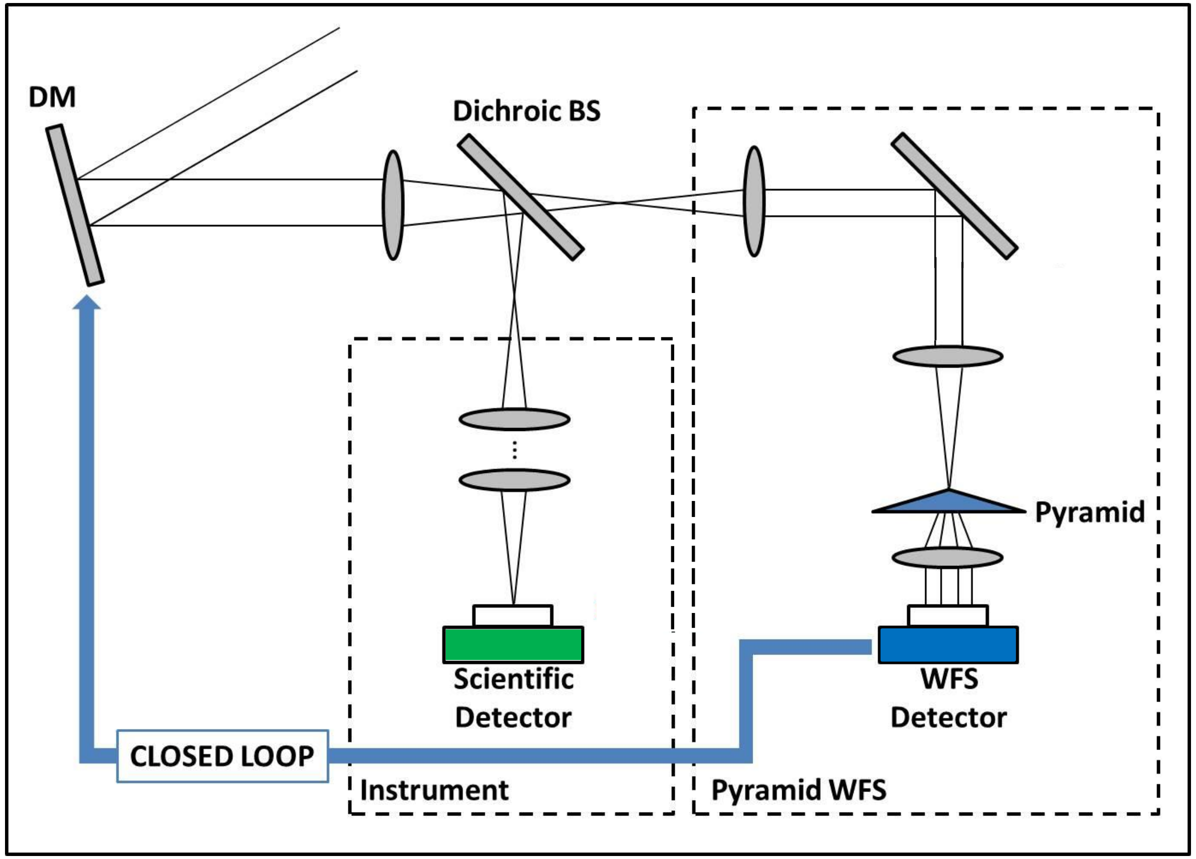
- *M. Quintavalla et al. "Adaptive optics on small astronomical telescope with multi-actuator adaptive lens", Proc. SPIE 10524 (2018)*

- It can be applied to existing instruments as it does not require an optical design modification.

  - Our idea: it can be used to remove NCPA (slow frequency) in SCAO systems, offering (theoretically) the diffraction limited PSF also to the WFS to improve the P-WFS performances.

  - Other ideas?

Concept

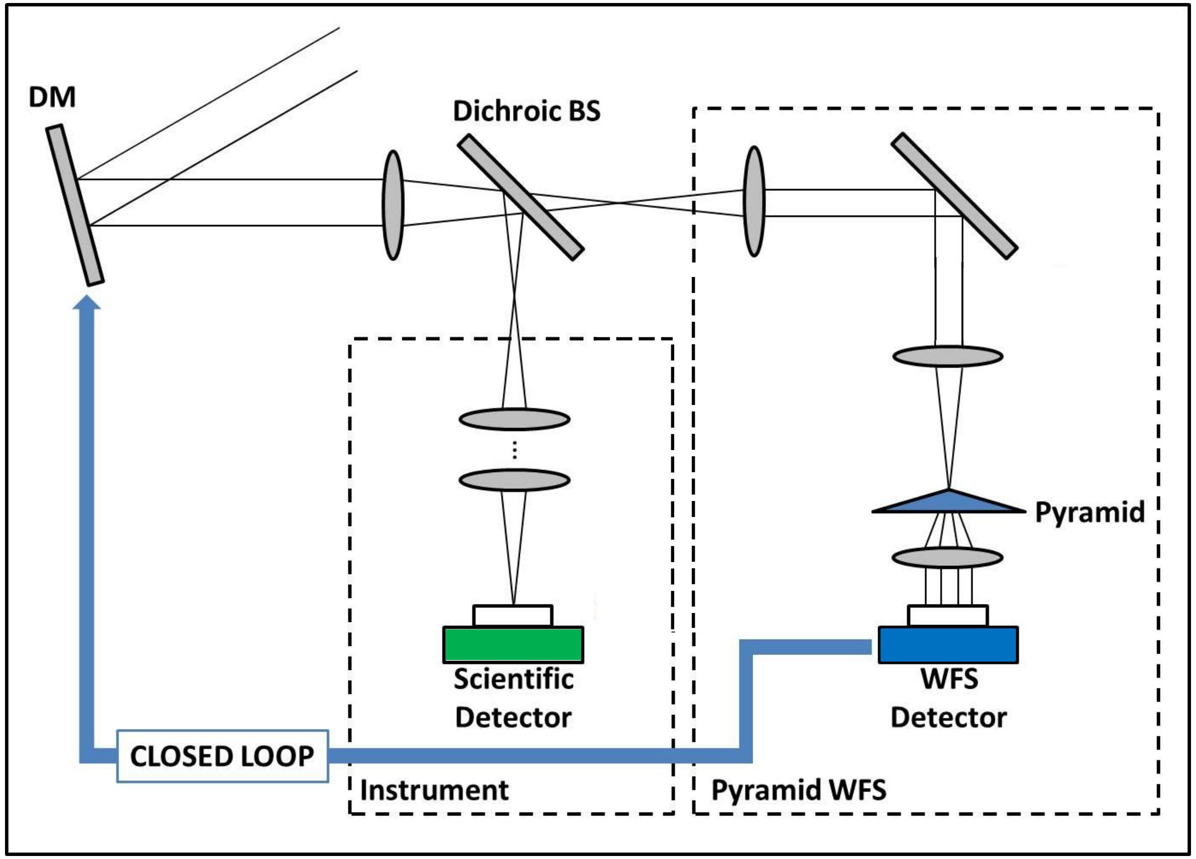


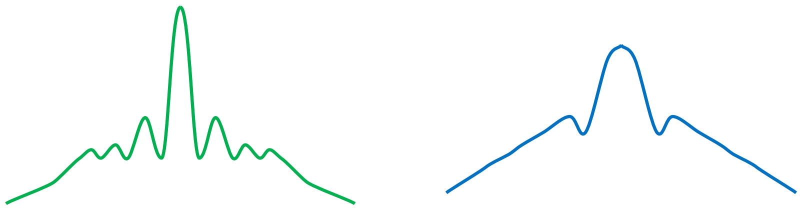
Common optical scheme of an astronomical instrument

NCPAs due to:

- poor relative alignment
- gravity
- thermal differential effects
- …

Concept

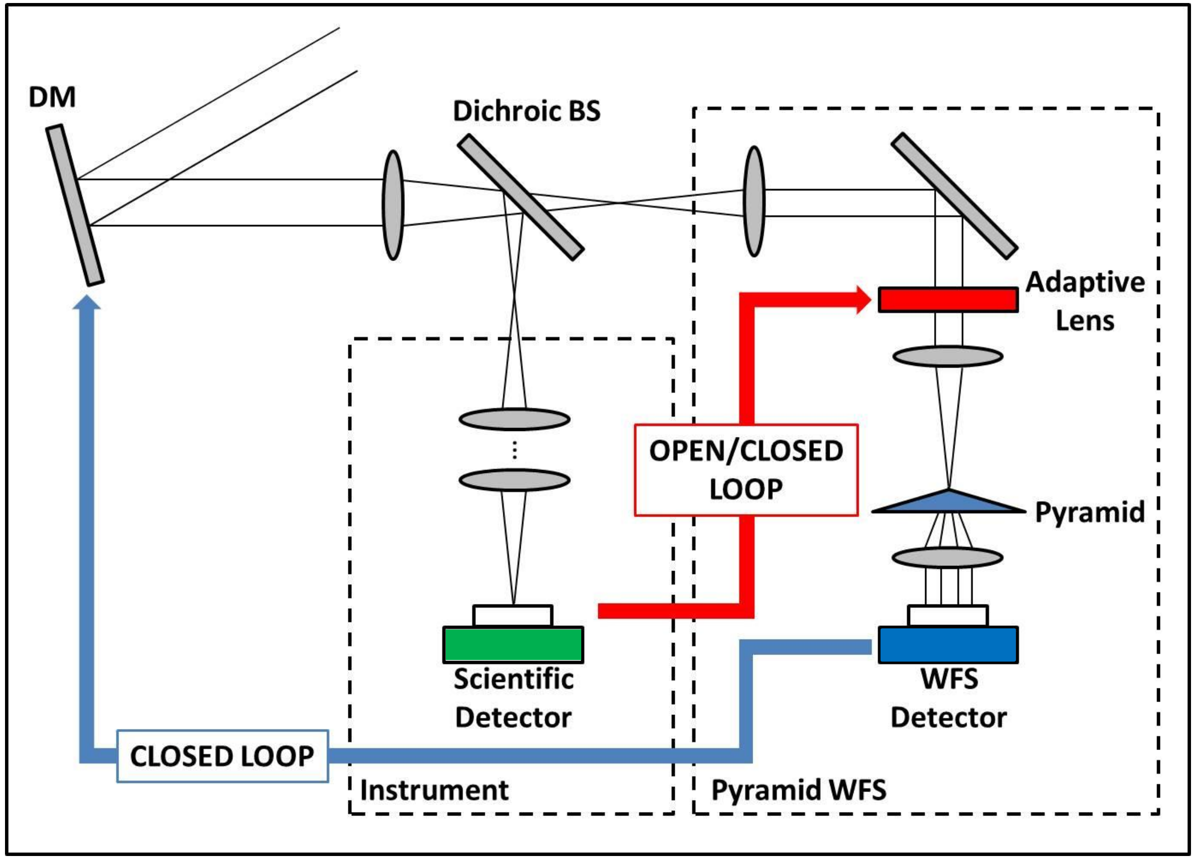


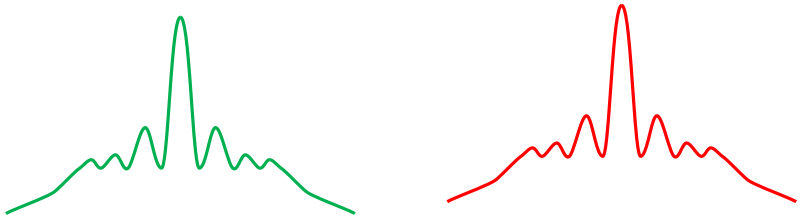


Common optical scheme of an astronomical instrument

We usually favour the scientific channel performances

Concept



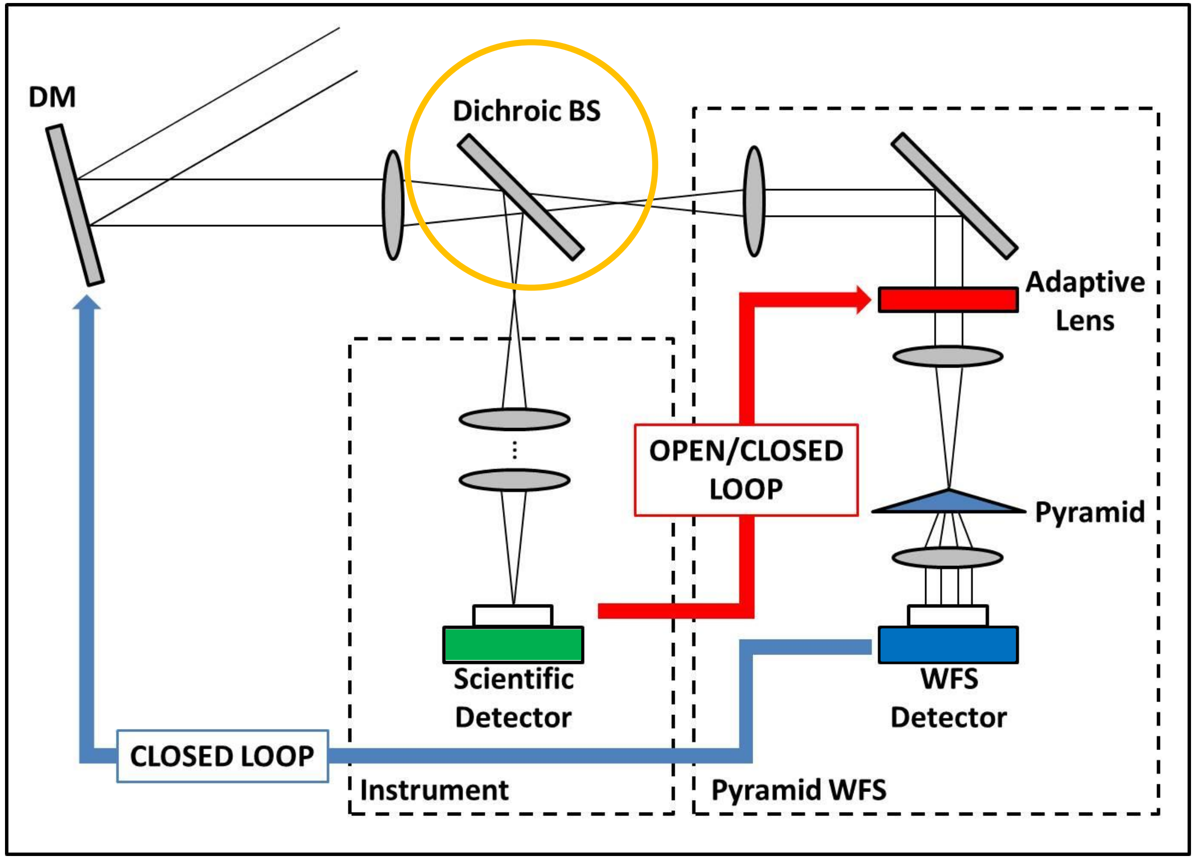


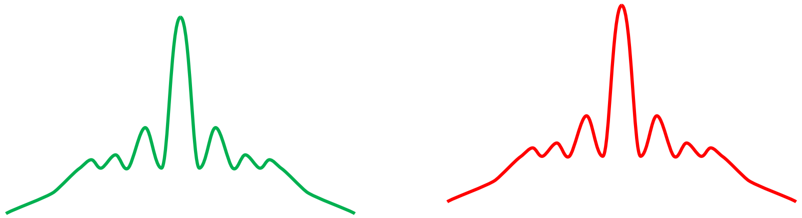
Common optical scheme of an astronomical instrument

We usually favour the scientific channel performances

Let's now give to the P-WFS similar performances with the MAL

Concept

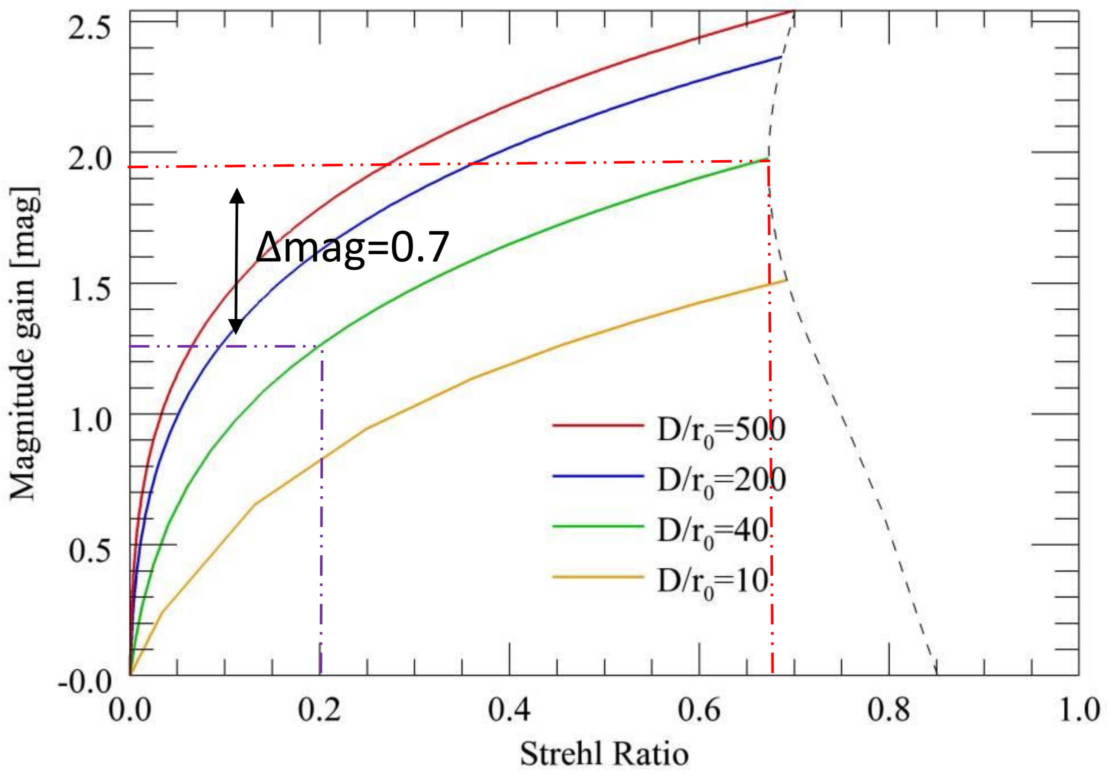




Dichroic contributes to most of NCPA in particular for astigmatism which is one of the modes best corrected by the MAL.

In the case of SHARK estimated NCPA:
0.2 waves rms (λ=633 nm)
Dichroic contribute: 0.15 waves rms

NCPA effect on P-WFS



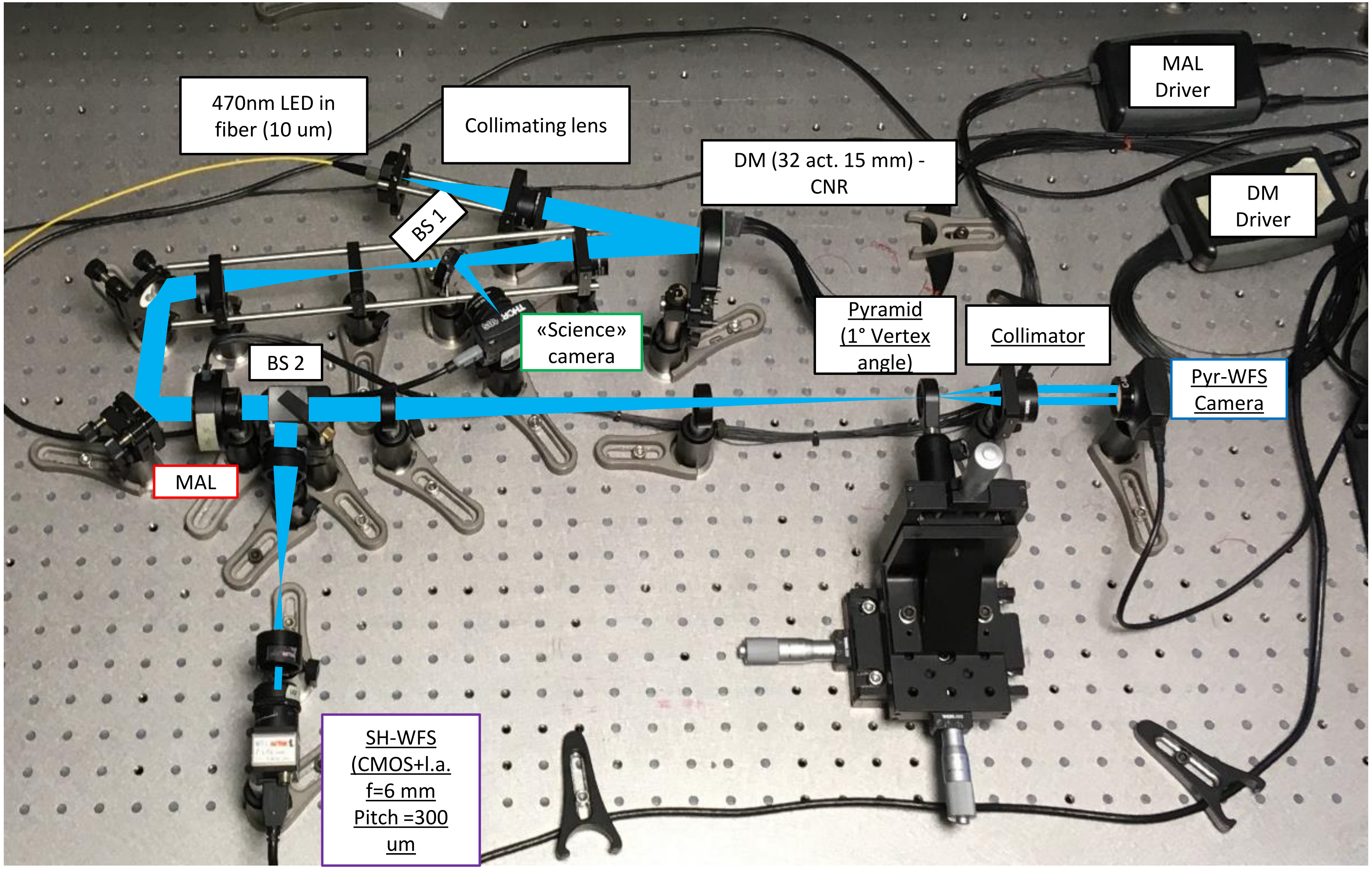
Viotto et al., 2016

Let's make some assumptions….

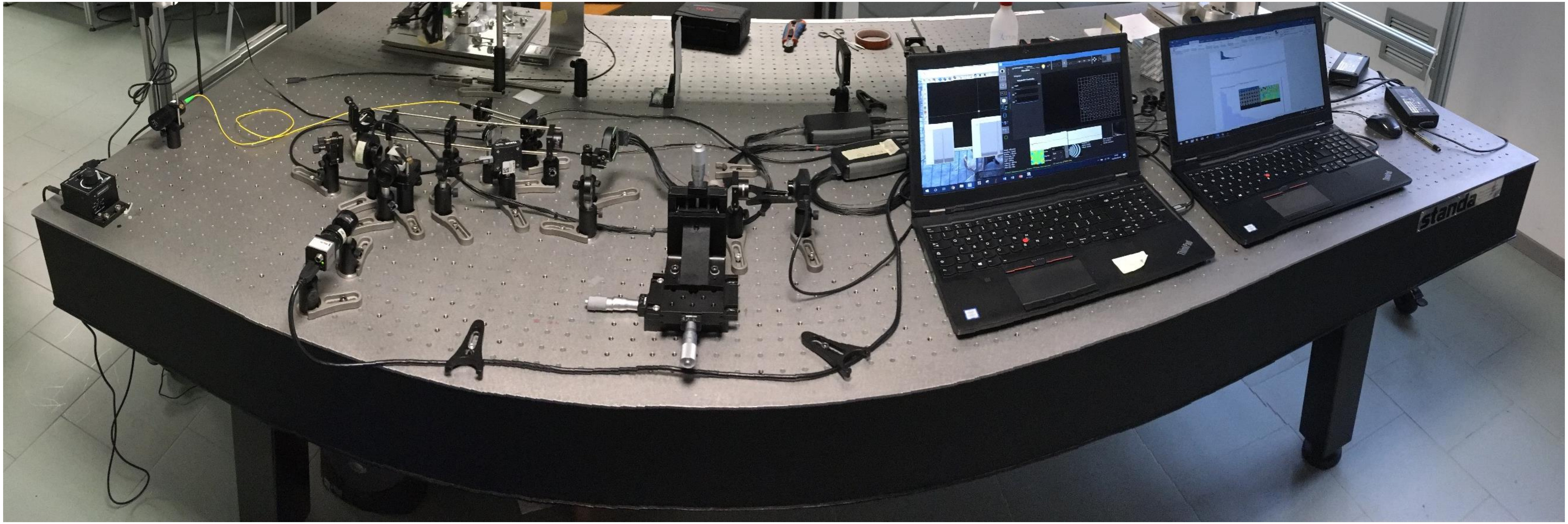
- 8-m telescope, with a P-WFS at visible wavelength: D/r_0=40
- Marechal approx SR= $e^{-(2\pi\sigma)^2}$
- Starting aberrations 0.2 waves rms → SR=0.2
- Reduction of NCPA down to 0.1 waves rms →SR =0.67

We could get 0.7 mag fainter star usable by the pyramid.

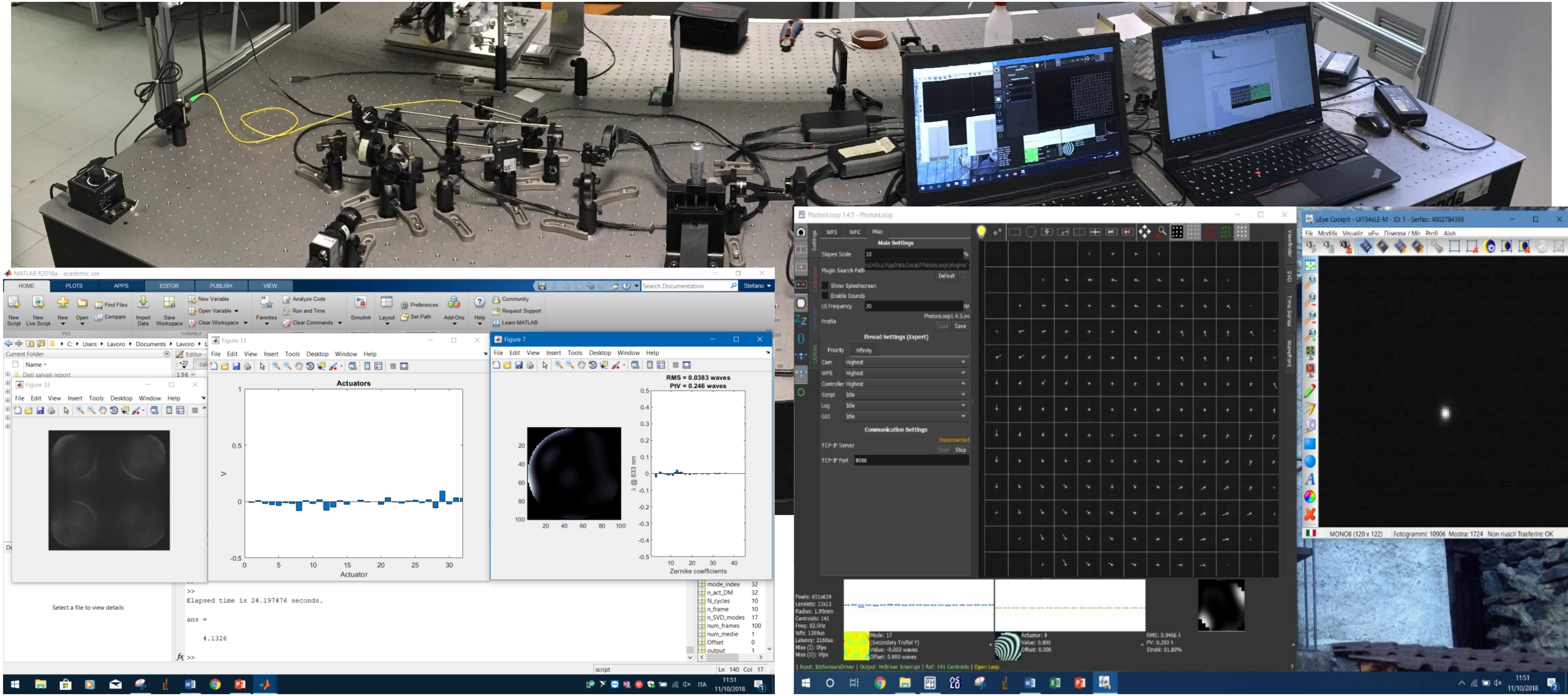
Test bench in the lab



Test bench in the lab



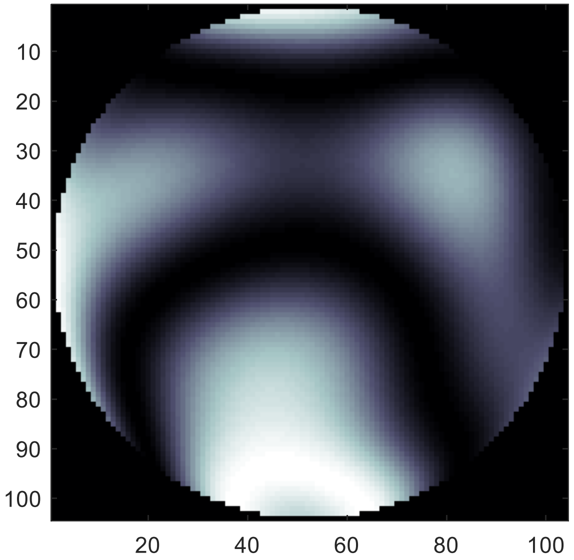
Test bench in the lab

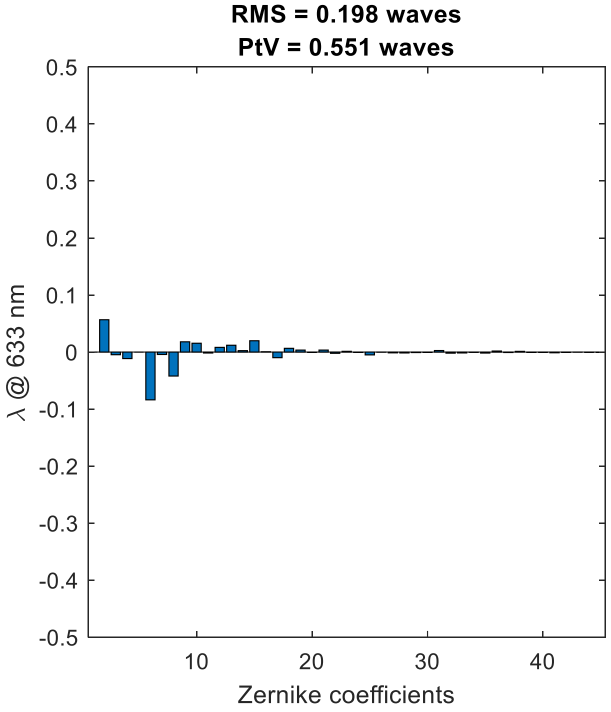


Closing the loop on the P-WFS with the DM (1)

Step#1: DM characterization in flat condition → essentially diffraction limited
Step#2: DM and MAL are in their rest condition

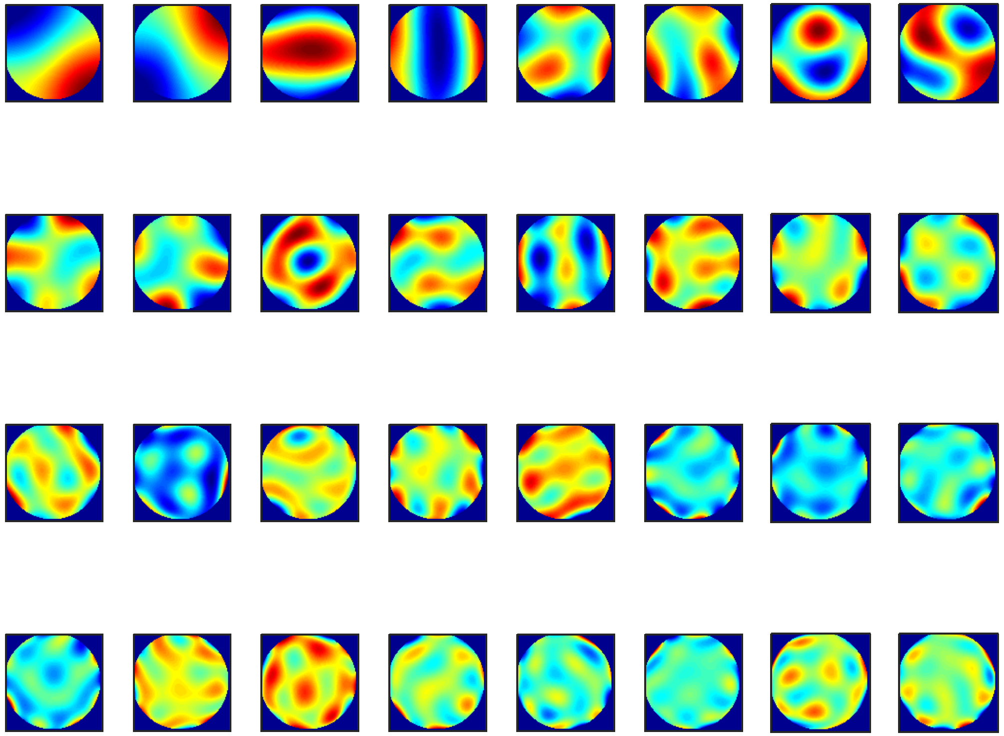
WF

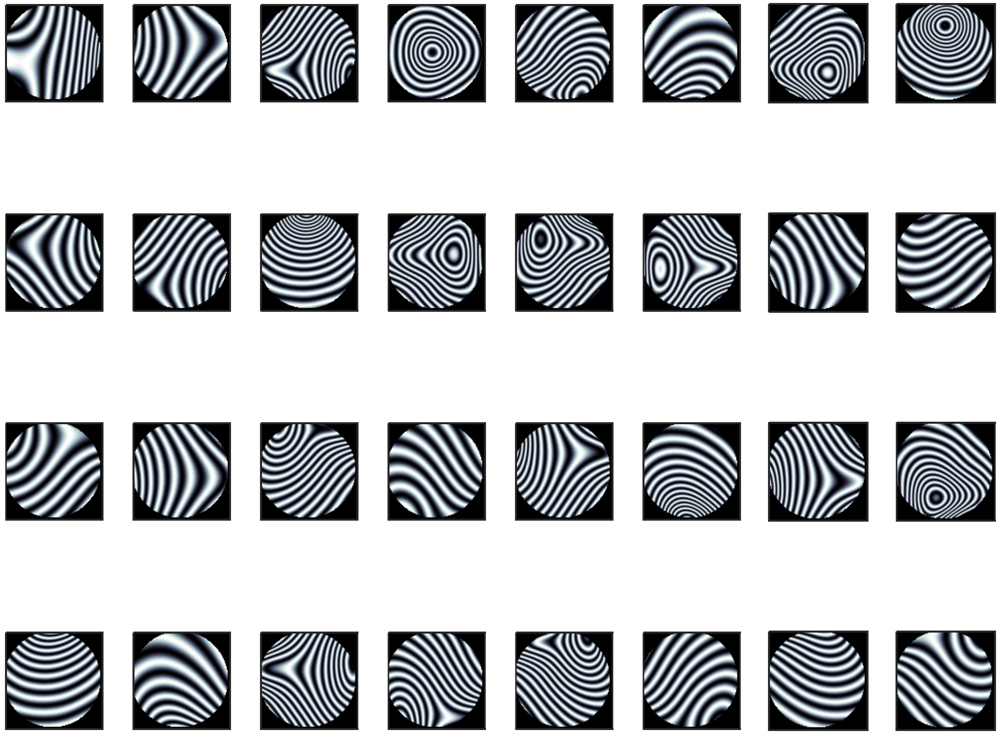




Closing the loop on the P-WFS with the DM (2)

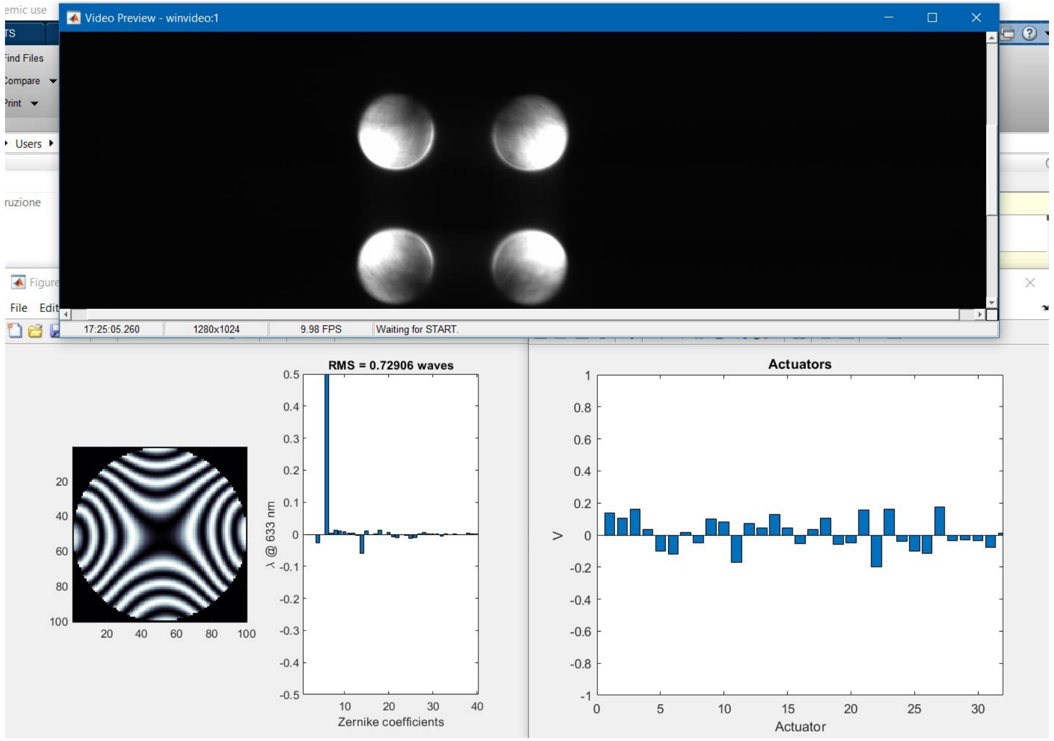
Step#3: DM influence functions acquisition and SVD modes of the DM using a 100 um core fiber.
Inverse matrix computation

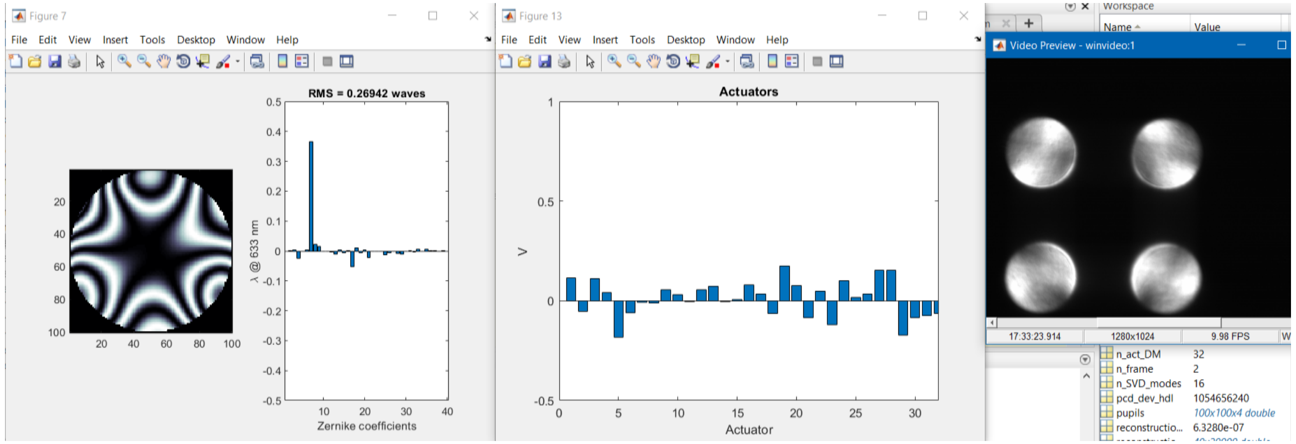


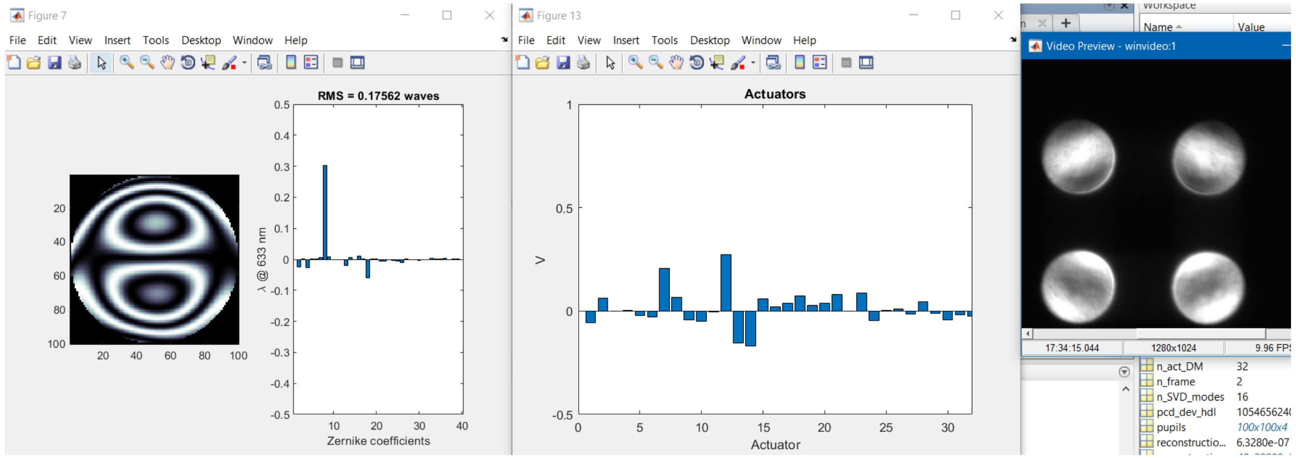


Closing the loop on the P-WFS with the DM (3)

Step#4: Introduce some offset to generate some Zernike polynomials and make sure everything seems reasonable

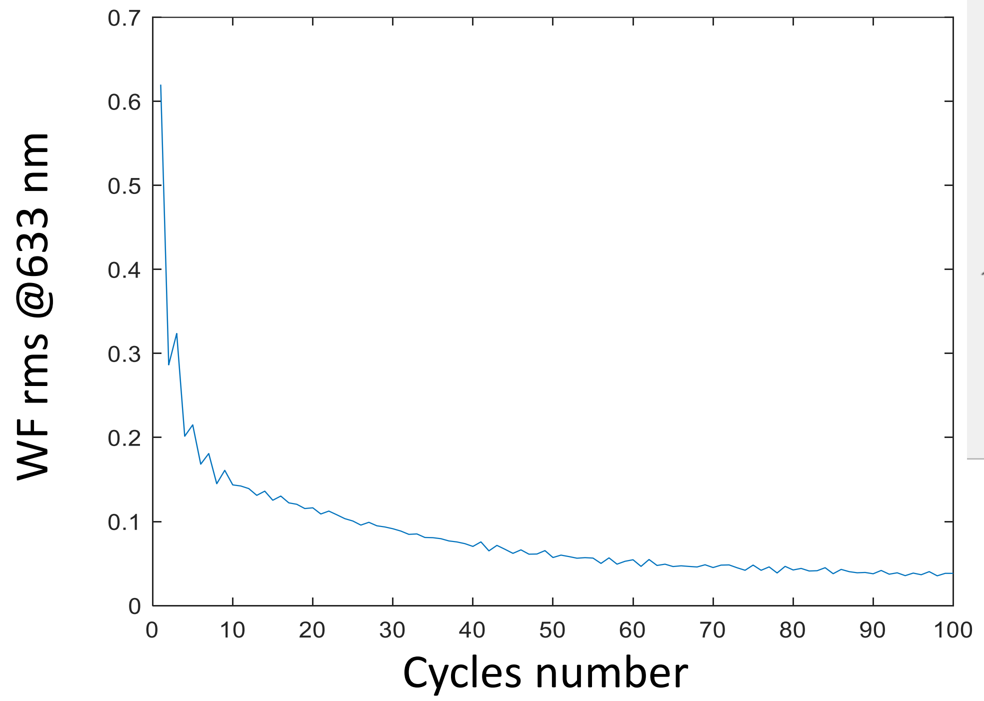


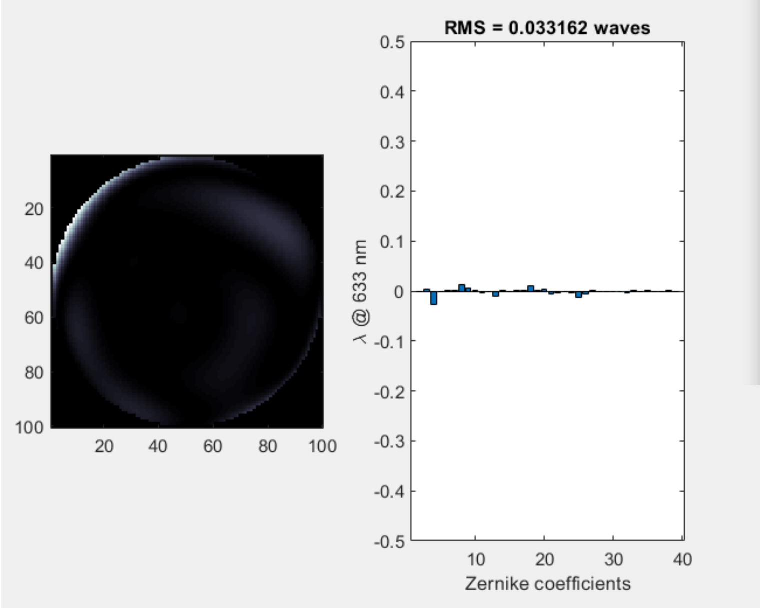


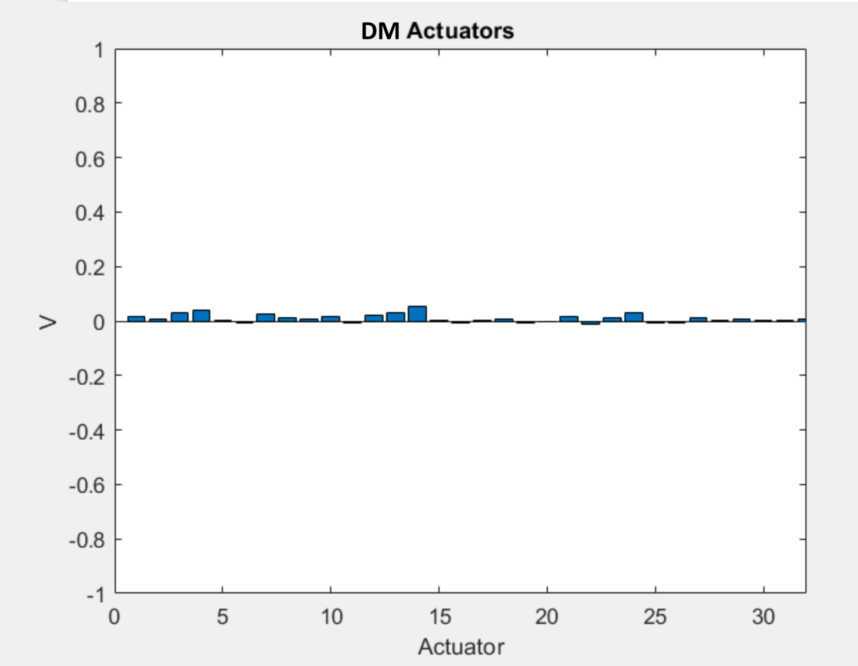


Closing the loop on the P-WFS with the DM (4)

Step#5: Insert 10 um fiber and apply gain (TT is about 10 times smaller than higher orders) and close the loop

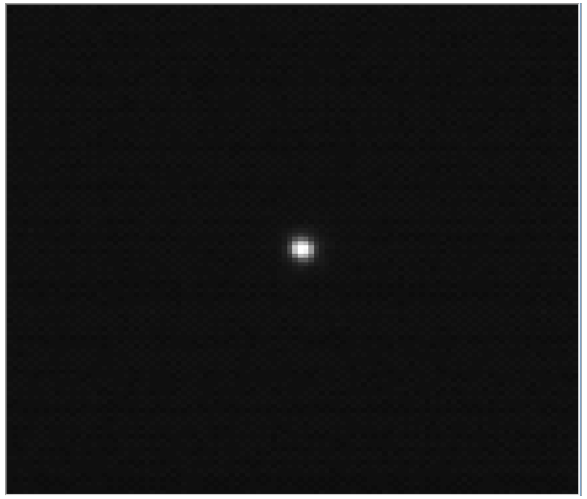




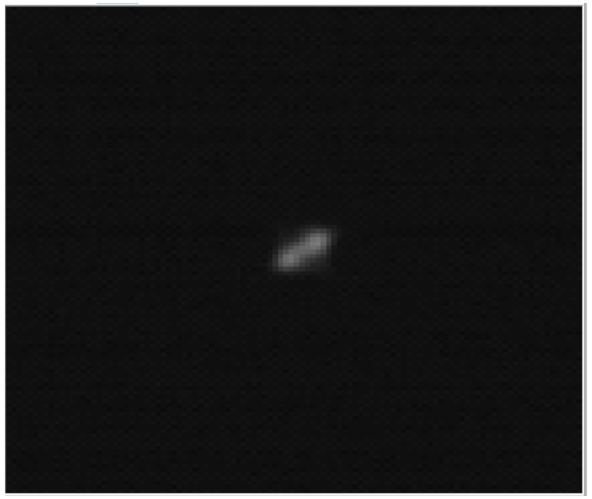


Modify the MAL shape to improve science PSF(1)

Step#1: prove that the PSF on the scientific camera changes accordingly to expectations

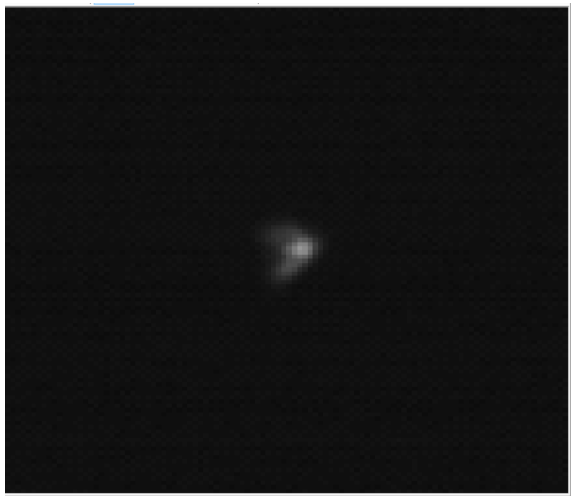


Starting PSF

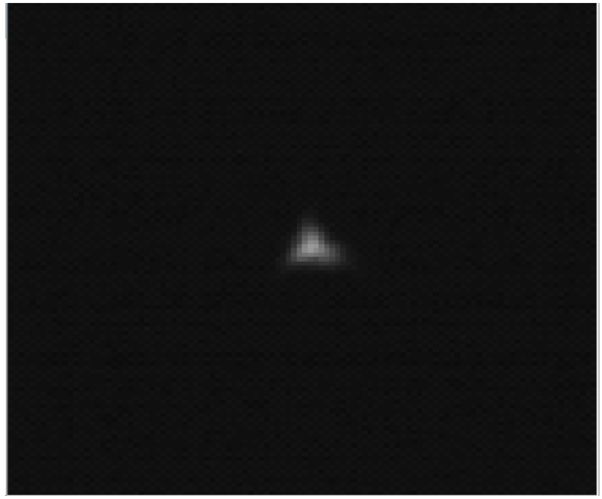


Astigmatism

+ defocus



Coma + defocus



Trefoil

(~ 0.3 waves rms per aberration)

Modify the MAL shape to improve science PSF(2)

Step#2: define a method to remove aberrations from the scientific PSF

Solution implemented (many others could be tested and used): image quality based metric (intensity) to iteratively tune the shape of the adaptive lens with an algorithm that optimizes each term of the Zernike.

- Apply a single aberration on the lens varying its amplitude step by step
  (e.g. defoucs term from -0.2 to 0.2 waves RMS in step of 0.04)
- Measure the PSF sharpness (we used the central second moment)

RESEARCH ARTICLE

Optimal model-based sensorless adaptive optics for epifluorescence microscopy

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1 Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands, **2** Flexible Optical B.V., Rijswijk, The Netherlands, **3** ITMO University, St Petersburg, Russian Federation

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Definition of image moments. Describing an image as a bidimensional distribution of light intensity $I(x, y)$ in a field of view F, its first moment, or center of mass, is defined as

$$\{m_{1x}(I), m_{1y}(I)\} = \left\{ \frac{\int_F I(x,y) \cdot x \, \mathrm{d}x \, \mathrm{d}y}{\int_F I(x,y) \, \mathrm{d}x \, \mathrm{d}y}, \frac{\int_F I(x,y) \cdot y \, \mathrm{d}x \, \mathrm{d}y}{\int_F I(x,y) \, \mathrm{d}x \, \mathrm{d}y} \right\}, \tag{5}$$

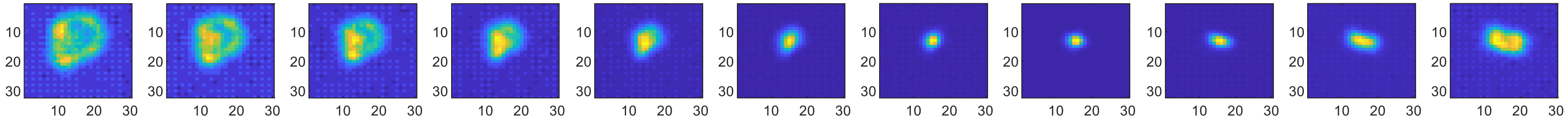
and the central second moment sm is defined as

$$\mathrm{sm}(I) = \frac{\int_F I(x,y)\left((x - m_{1x}(I))^2 + (y - m_{1y}(I))^2\right) \mathrm{d}x \, \mathrm{d}y}{\int_F I(x,y) \, \mathrm{d}x \, \mathrm{d}y}. \tag{6}$$

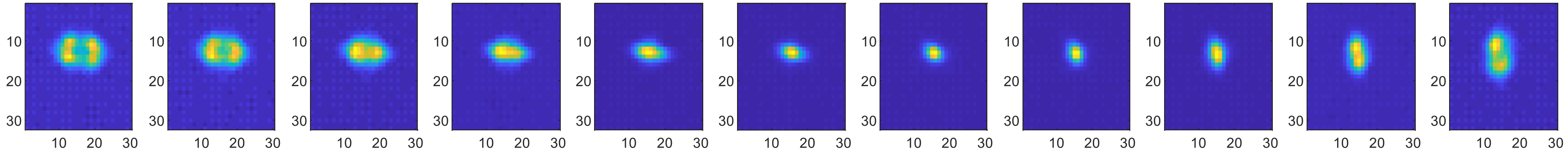
Modify the MAL shape to improve science PSF(3)

Step#3: tune the MAL aberrations to shrink PSF

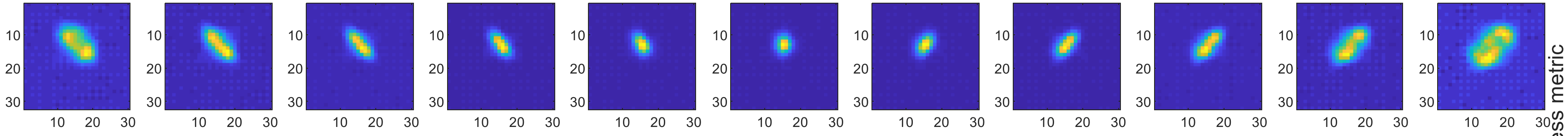
Astigmatism

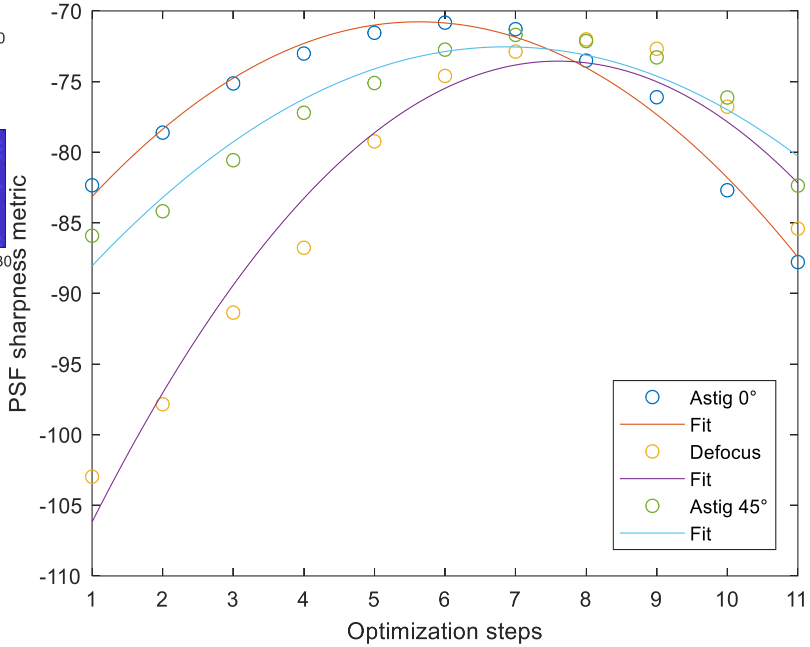


Focus



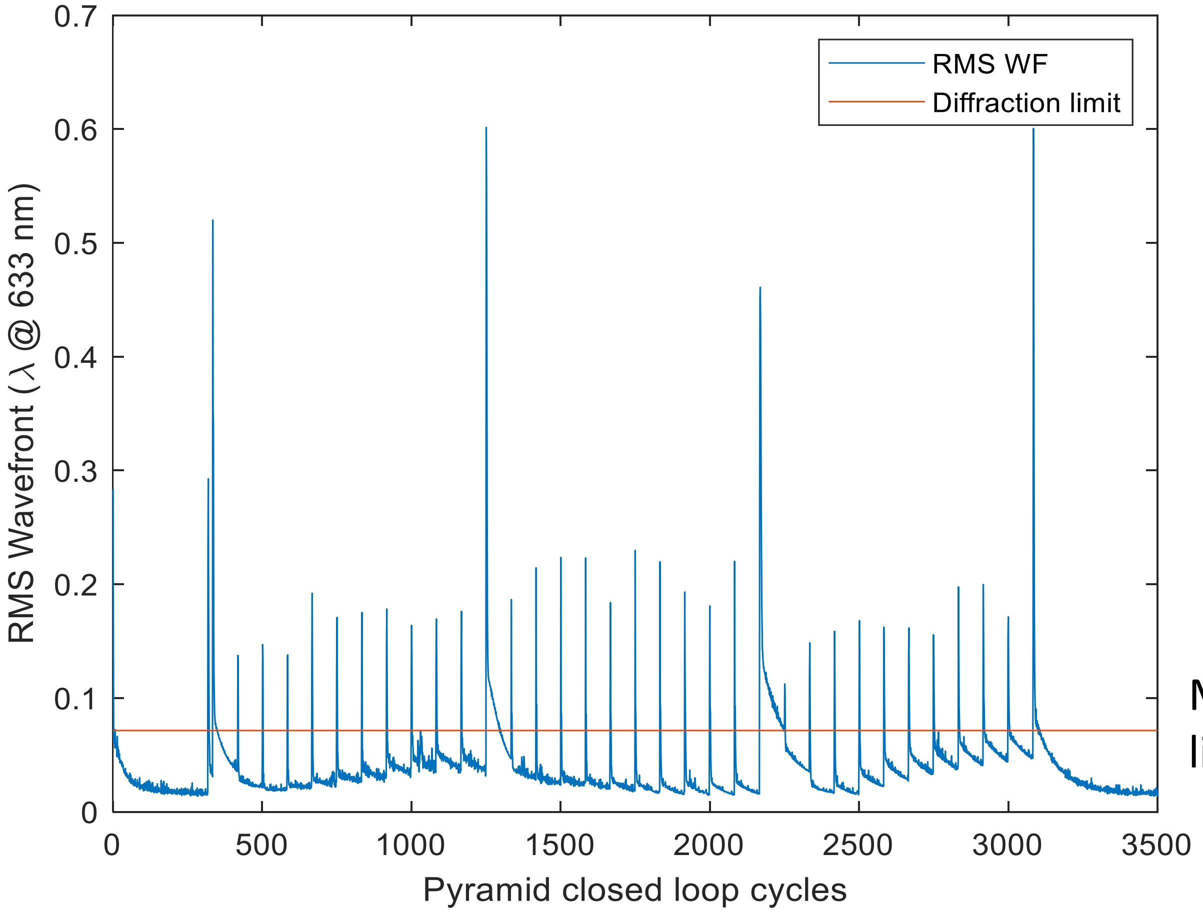
Astigmatism 45°





Modify the MAL shape to improve science PSF(4)

Step#4: check the RMS measured by the pyramid during the process (spikes correspond to lens shape variations)



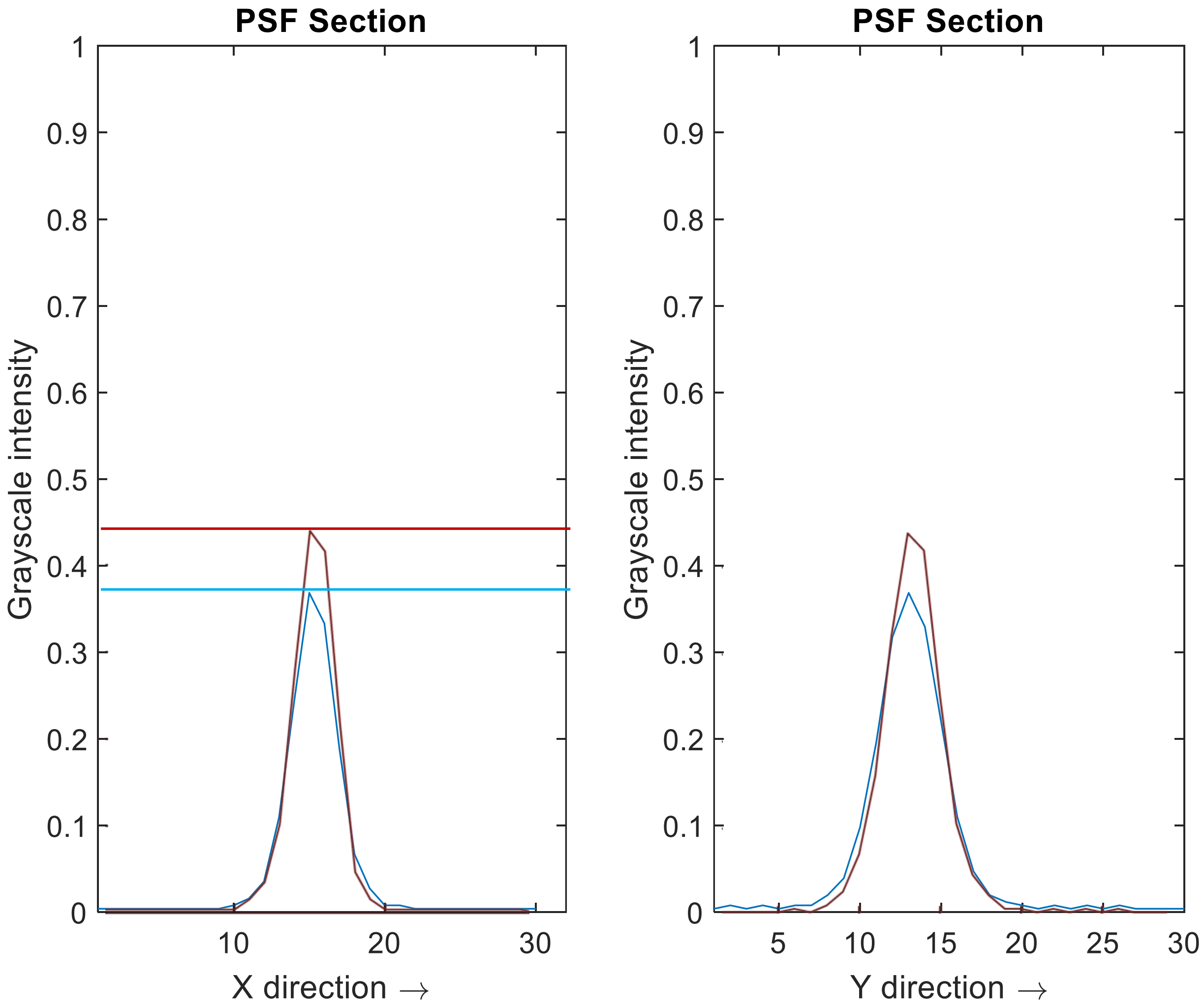
Marechal diffraction limit: λ/14 @ 633 nm

Modify the MAL shape to improve science PSF(5)

Step#5: analyze the PSF improvement

Last second test was the right one

We have an increase of about 10% in the peak and assuming it is energy transferred in the PSF core, we can infer that the SR improved by 10%



Conclusions & Next steps

LAB test:

- Preliminary lab tests were shown and seems promising
- Stability over time of MAL needs to be characterized
- SH-WFS in the place of the scientific detector to better estimate the image quality and correct the PSF

MAL development:

- Trade some dynamical range (from 10 waves down to 1) to some sensitivity in the applied deformations
- Full characterization in terms of transmissivity, chromatic aberrations, stroke and correction residuals
- Investigate faster frequencies (from 200 to 500-1000 Hz) to test modulation

On-sky tests:

- On-sky demonstration of the concept

CANARY

- Installation of the lens in an already existing instrument with a pyramid WFS to actually assess the improvement

Thanks a lot for your attention!!!

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LABORATORIO NAZIONALE ADONI OTTICA ADATTIVA