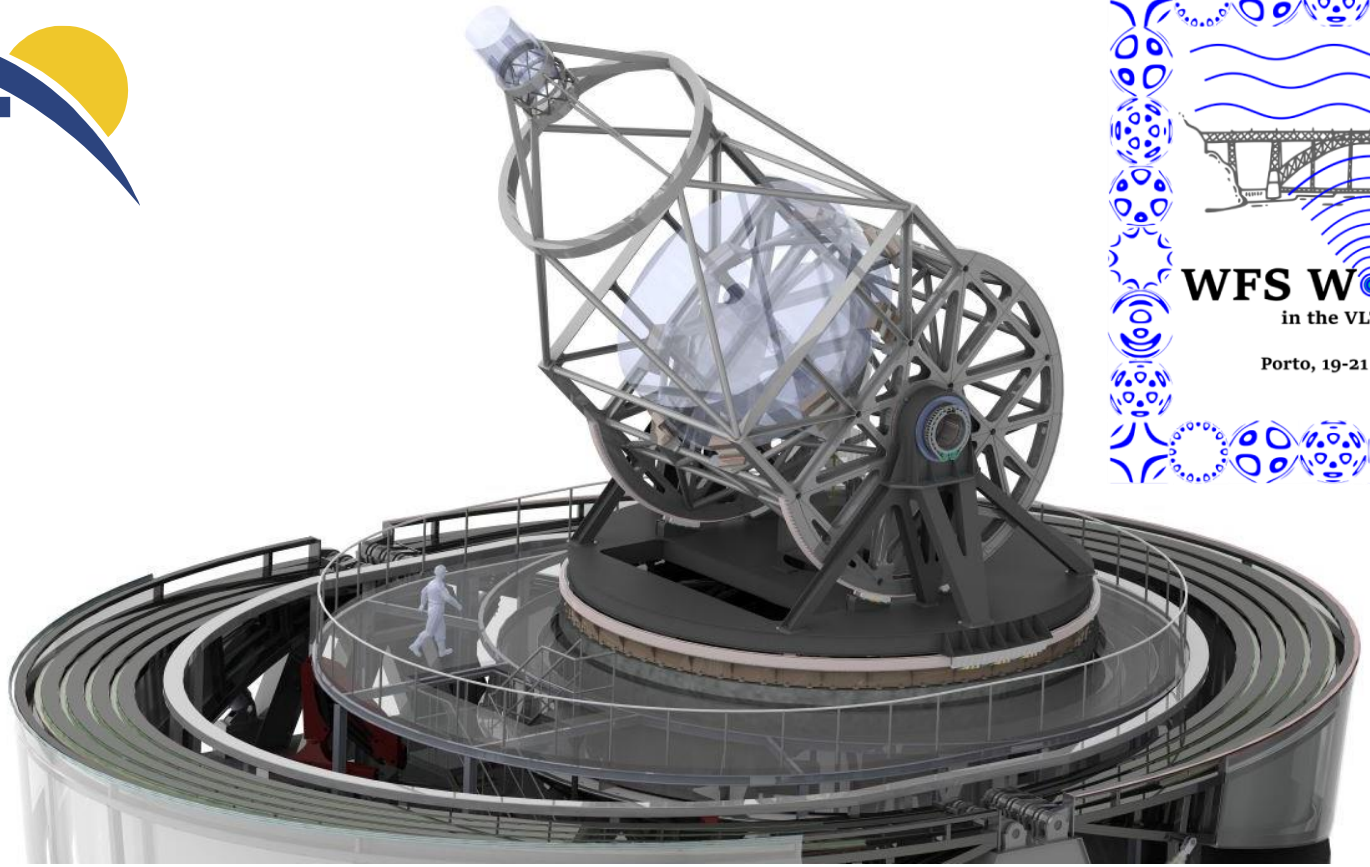


# Study of wavefront sensing strategies for the future EST based on laboratory results.

**Luzma Montoya, , Jose Manuel González, Yolanda Martín, Noelia Feijoo, Haresh Chulani, Francisco González, Jorge Quintero**

***Instituto Astrofísica de Canarias***

*"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 739500"*

European Union
European Regional Development Fund

# CONTEXT

The EST is a **4-metre** solar telescope optimised for studies of the magnetic coupling between deep photosphere and upper chromosphere.

- High spatial resolution.
- High temporal resolution.
- FOV 60” (500nm - 2200nm)

- MCAO: Multi-conjugate adaptive optics.
  - Strong turbulences concentrated in a few prominent layers, specially in the low altitudes.

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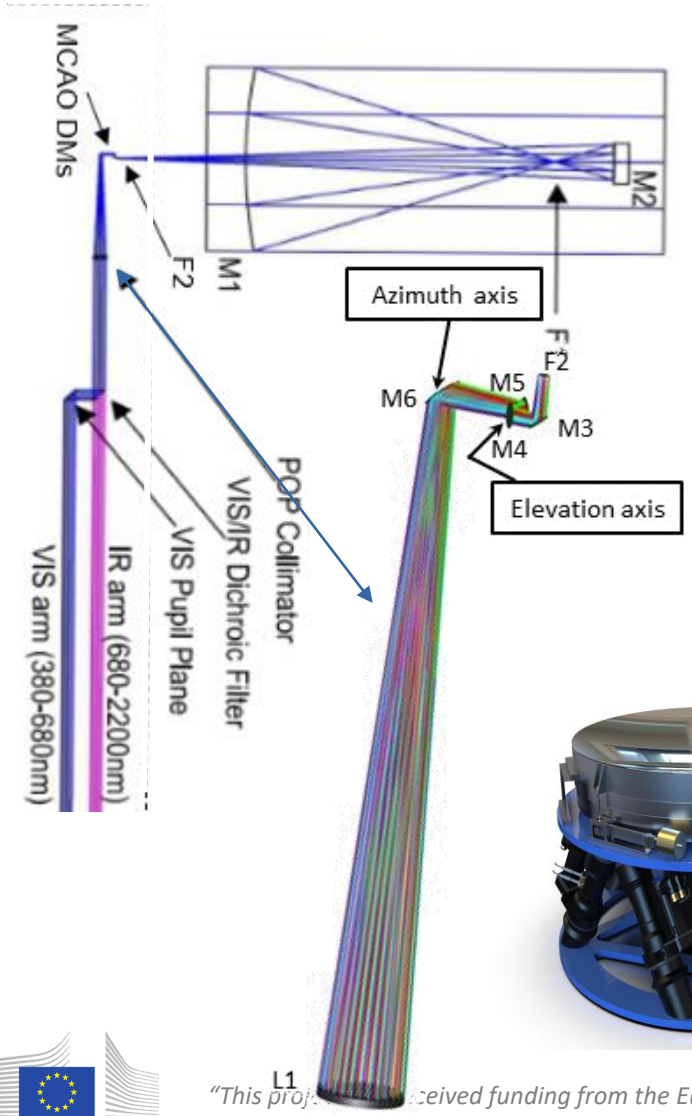
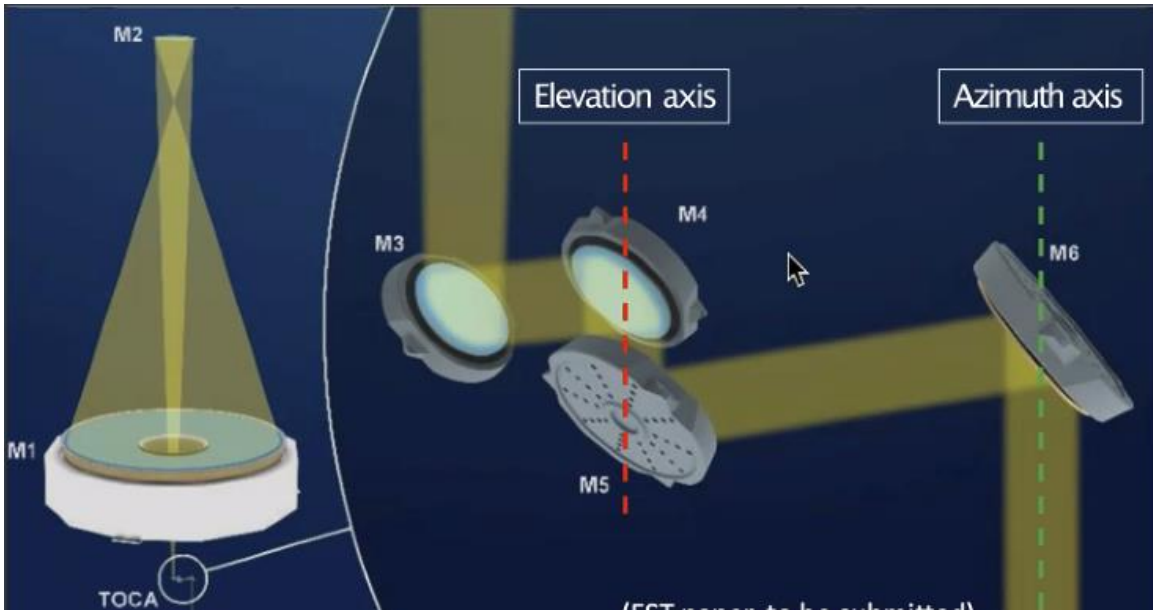
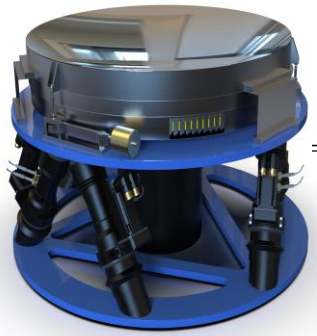
# Optical Design EST: MCAO




| Physical properties: diameter, mass | | Optical prescription | |
|---|---|---|---|
| Actuation aperture: | ⌀= 800 mm | Shape: | concave ellipsoid |
| Mass: | < 750 kg | Curvature Radius: | 2156.4 ± 1.0 mm |
| Eigenfrequency: | > 50 Hz | Conic constant: | -0.6344 ± 0.0003 |
| | | Coating optimized at: | 850 nm |



**Number of actuator 2000, pitch 16.2mm**
**Slow positioning ± 10mm**
**Fast positioning ± 85µm**



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# Test-bed EST: Objectives

- Select the **optimal configuration for solar MCAO** based on the performance results obtained in a realistic environment.
- Study the effect of the **order of the deformable mirrors** in the MCAO performance.
- Study the feasibility and performance improvements achieved using **DMs with adjustable conjugate heights**.
- Study the impact of using **DM oriented at 45º on the MCAO** system, including the variation of the conjugated height in the DM surface and the anisotropic actuator distribution.
- Study the **pupil misregistration effects** caused by using intermediate DM between a DM a WFS.
- Study the impact of the **pupil rotation and spider footprint** on the wavefront sensing and reconstructor.
- Implement Artificial Neuronal Network (**ANN**) in the reconstruction and control of the MCAO system and study their suitability and performance.
- Define, implement and validate different **calibration procedures** that can be used with a deformable secondary mirror in order to select the optimal procedure for the EST.

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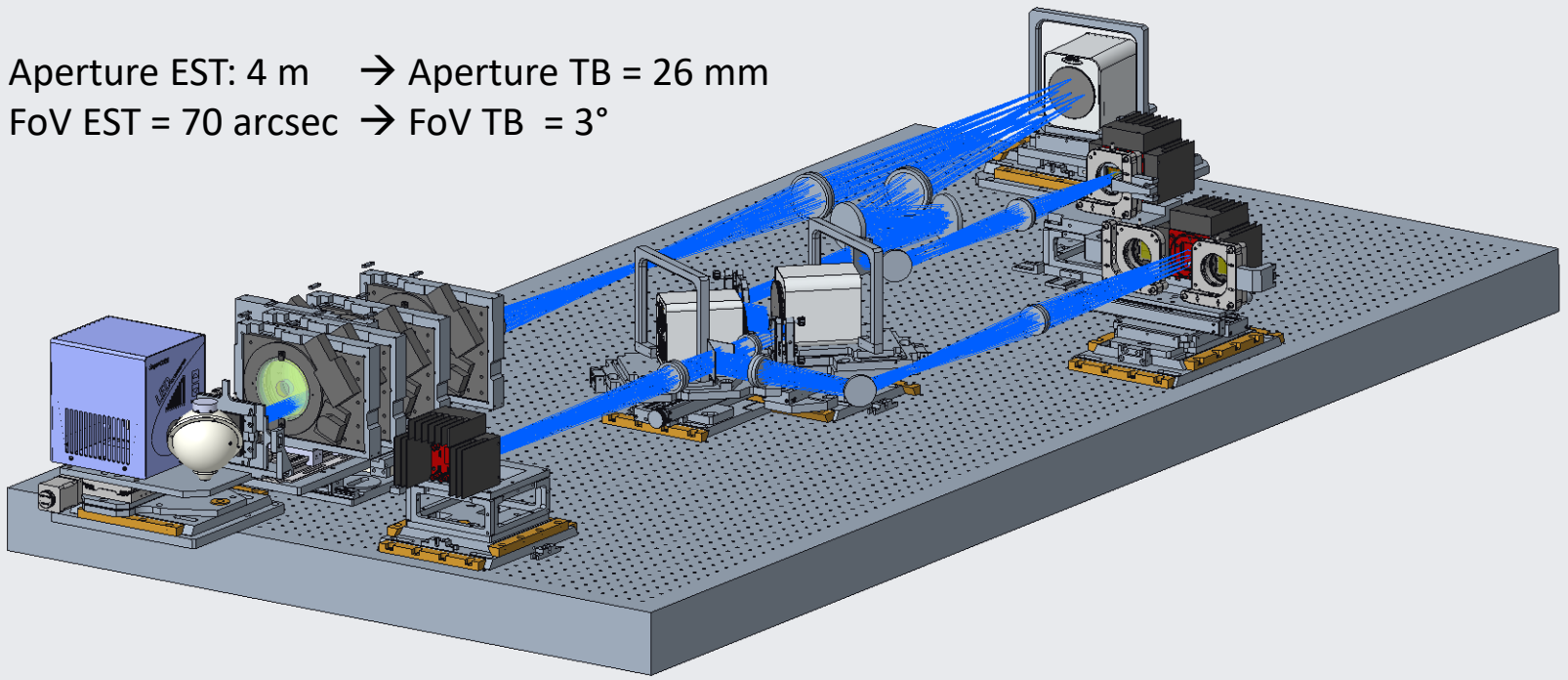
# Test-bed EST:MCAO concept

| | |
|---|---|
| r0 > 10cm & FoV ≤ 30” | SR ≥ 0.25 |
| r0 > 10cm & 30” ≤ FoV ≤ 60” | SR ≥ 0.15 |
| r0 > 20cm & FoV ≤30” | SR ≥ 0.4 |
| r0 > 20cm & 30” ≤ FoV ≤ 60” | SR ≥ 0.3 |

Aperture EST: 4 m → Aperture TB = 26 mm
FoV EST = 70 arcsec → FoV TB = 3°



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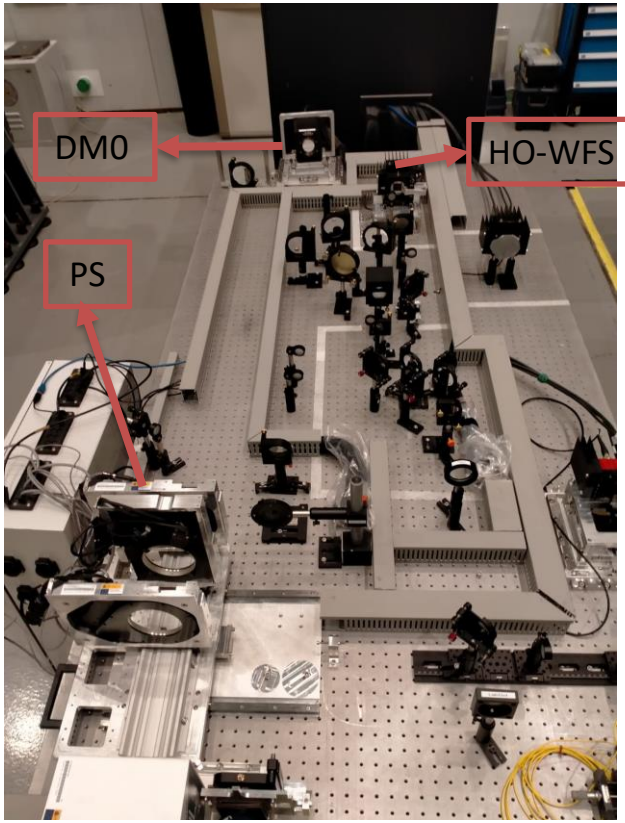
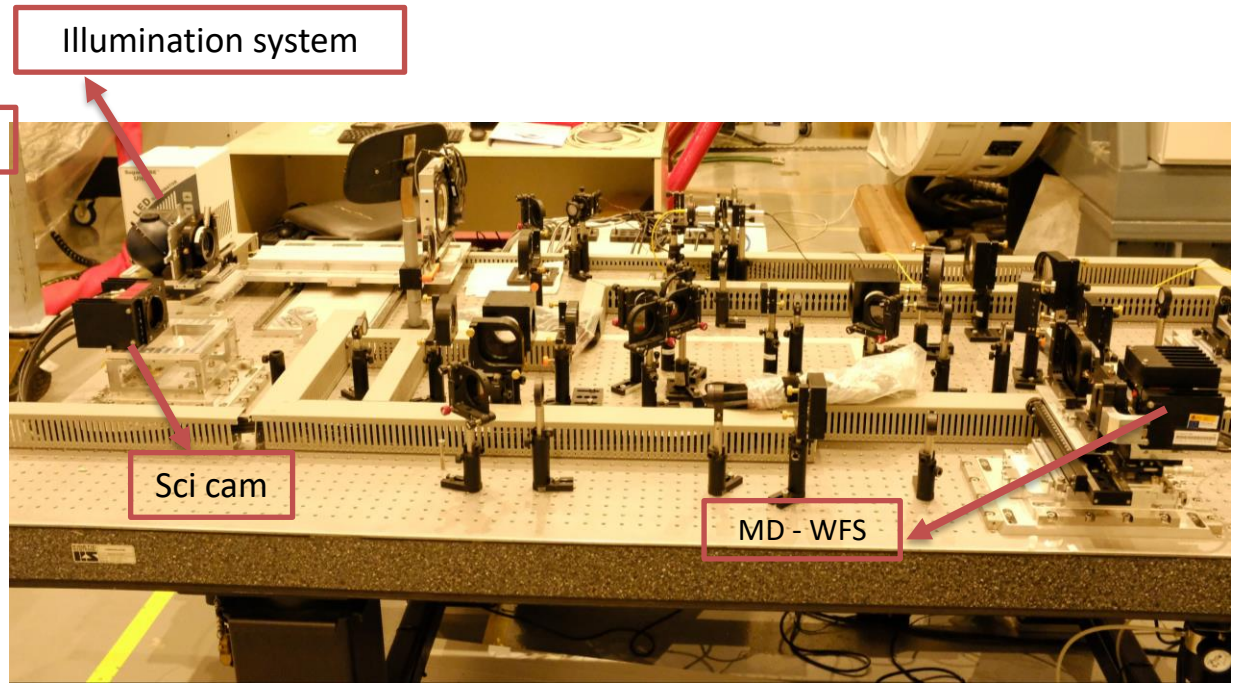
# Test-bed:Optical setup

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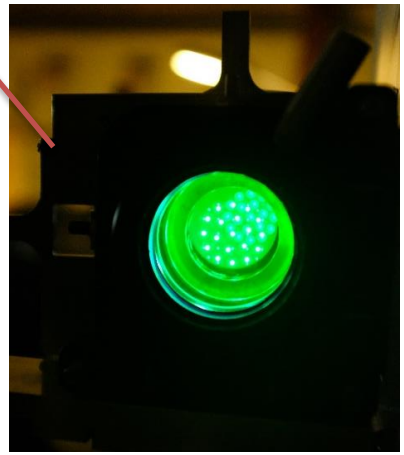
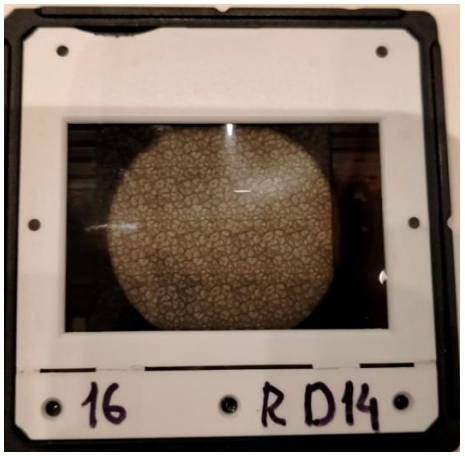
# Test-bed:Illumination System

19 Pinholes 0.4''(150 µm) **WFS**
25 Pinholes 0.026'' (10 µm) ) **Science camera**

Pinholes Array

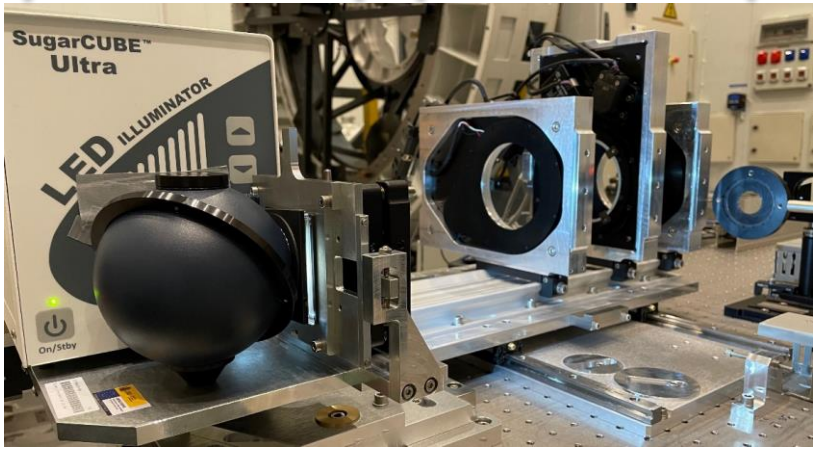


Sun object:
granulation and sun spot

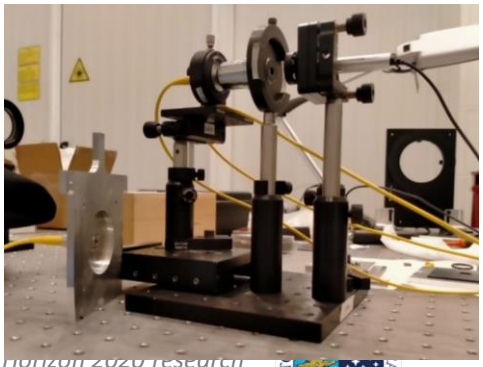



Illumination Sytem

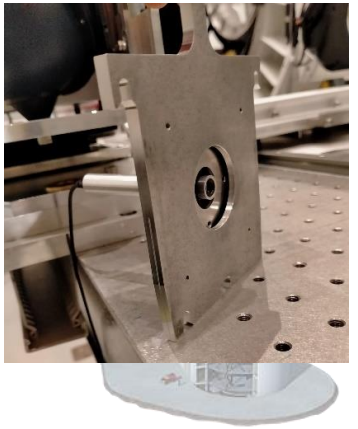
Turbulence Simulator




Fiber (532nm)



Aligment laser



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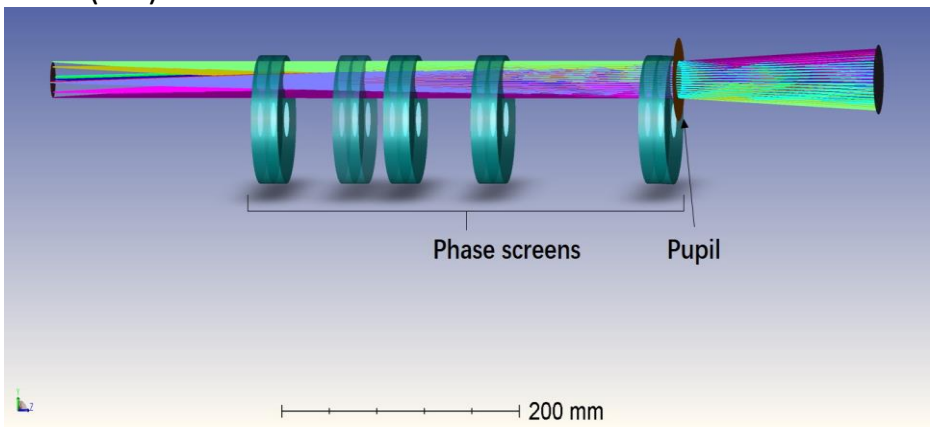
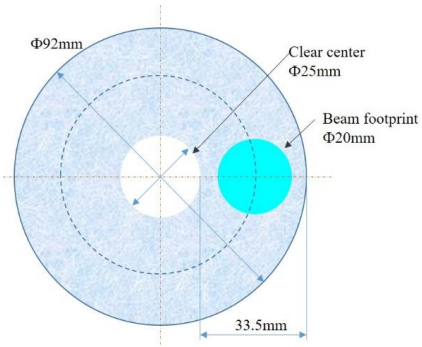
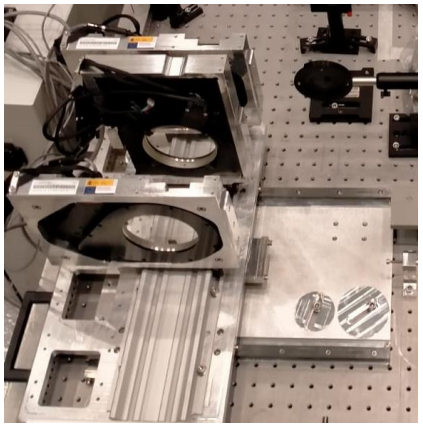
# Test-bed:Turbulence Simulator

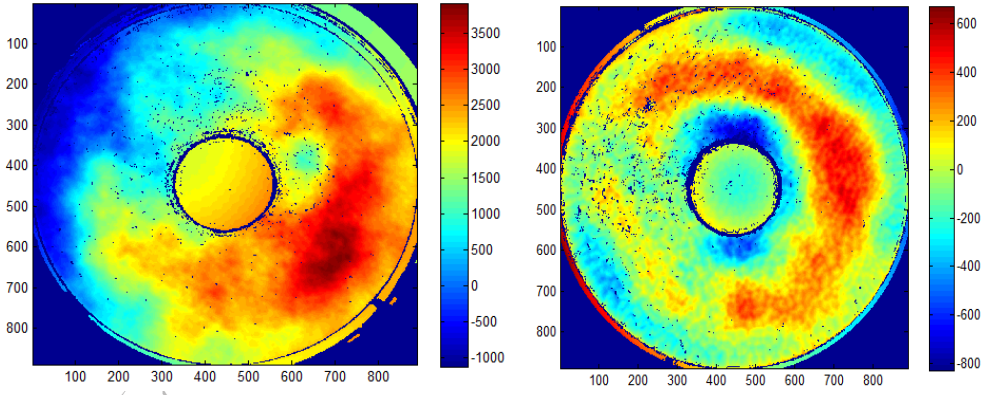
H (Km): 20 12 9 5 0



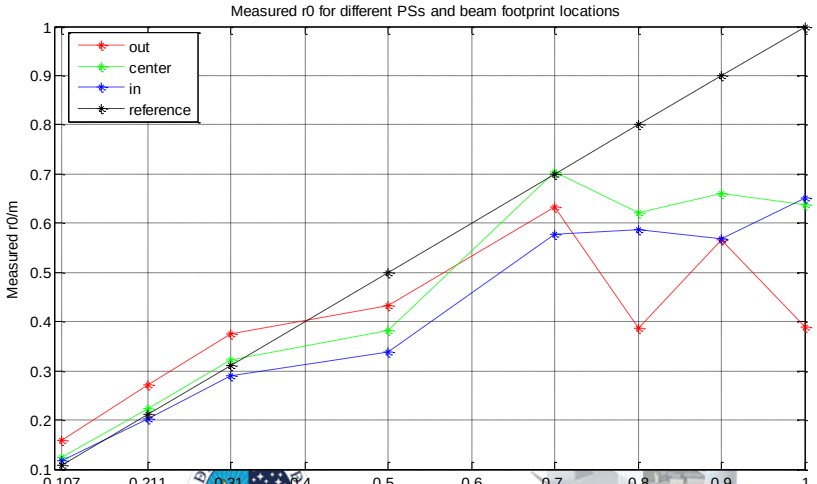
Measurements PS with Zygo interferometer



R0 = 20 cm

R0 = 90 cm

Measurement PS with GTCAO

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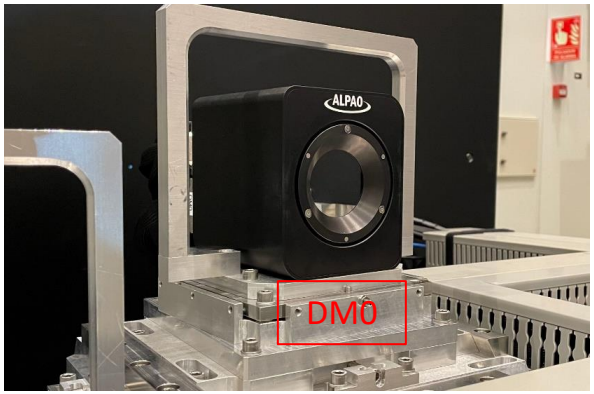
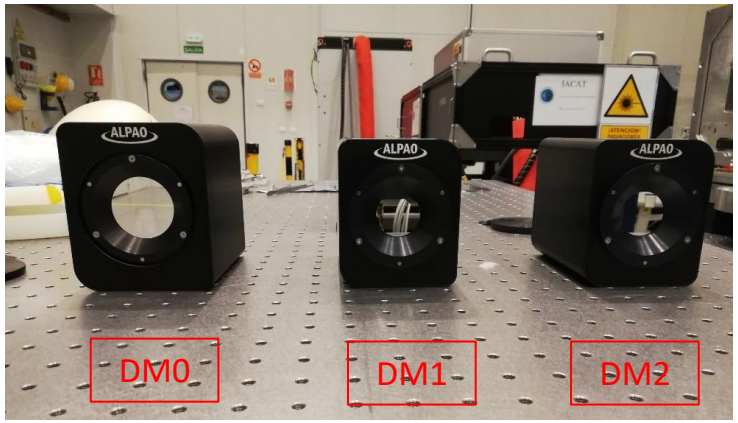
# Test-bed:DMs




| DM0 | | |
|---|---|---|
| SIZING | Number of actuators | 820 |
| | Pupil diameter (mm) | 45 |
| | Pitch (mm) | 1.5 |
| | Number of actuators across the diameter | 32 |
| QUALITY | Active best flat (nm RMS, mechanical) | < 7 |
| STROKE | Tilp/TilT strolke (µm P-V, wavefront) | 12 |
| | Defocus Astis. stroke(µm P-V, wavefront) | 10 |
| | 3x3 stroke(µm P-V, wavefront) | 10 |

| DM1 & DM2 | | |
|---|---|---|
| SIZING | Number of actuators | 468 |
| | Pupil diameter (mm) | 33 |
| | Pitch (mm) | 1.5 |
| | Number of actuators across the diameter | 24 |
| QUALITY | Active best flat (nm RMS, mechanical) | <7 |
| STROKE | Tilp/TilT strolke (um P-V, wavefront) | 12 |
| | Defocus Astis. stroke(µm P-V, wavefront) | 10 |
| | 3x3 stroke(µm P-V, wavefront) | 10 |

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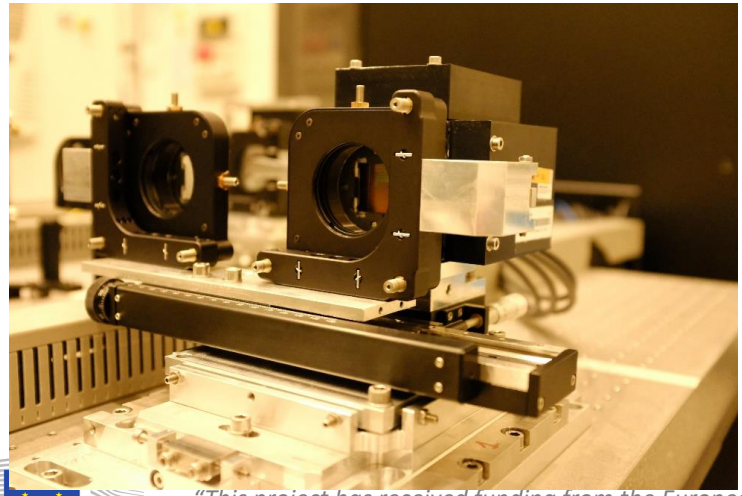
# Test-bed:WFSs

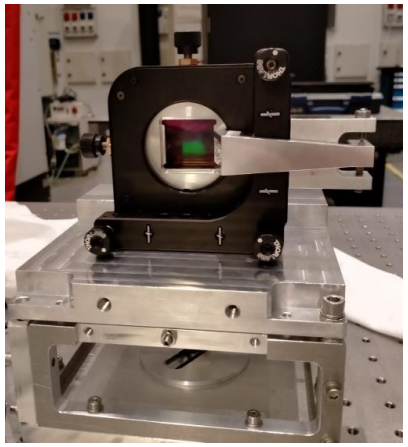
| | |
|---|---|
| Substrate Material | UV Fused Silica |
| Square Lens Array | spherical lens / square aperture |

| HO - WFS | |
|---|---|
| Optic Total Clear Aperture | 13.695mm x 13.695mm |
| Lenslet EFL | 26.03mm |
| Lenslet array | 33 x 33// 0.25”/px |
| FoV | 10 ”— 40 px |

HO – MD –WFS & MD - WFS



HO –WFS



| HO – MD –WFS | |
|---|---|
| Optic Total Clear Aperture | 27.291mm x 27.291m |
| Lenslet EFL | 16.17mm |
| Lenslet array | 33 x 33 // 0.4”/px |
| FoV | 70 ”—175px |

| MD –WFS | |
|---|---|
| Optic Total Clear Aperture | 27.302mm x 27.302m |
| Lenslet EFL | 21.53mm |
| Lenslet array | 17 x 17 // 0.3”/px |
| FoV | 70 ”—233px |

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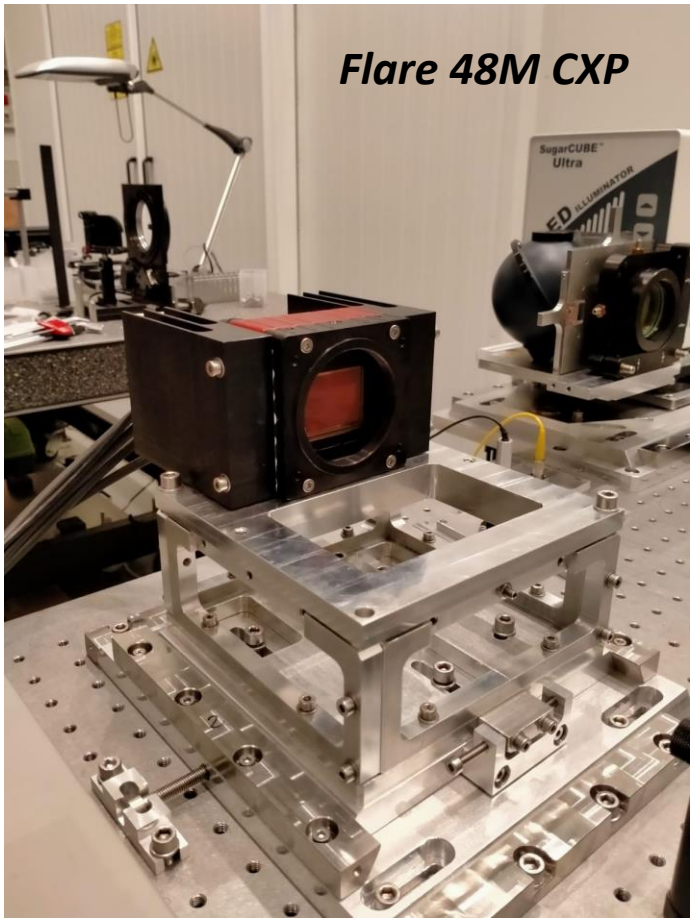
# Test-bed: Science Camera

| Sensor | CMOSIS CMV50000 |
|---|---|
| Effective Pixels | 7920 x 6004 |
| Optical Format | 35mm full frame |
| Pixel Pitch | 4.6 x 4.6 $\mu m^2$ |
| Full Well Charge | 14.5 ke- normal mode<br>58 ke- binning mode |
| Conversion | Gain 0.27 DN/e- normal mode<br>0.068 DN/e- binning mode |
| Responsivity | 0.16 DN/ph |
| Temporal Noise | 8.8 e- Normal mode<br>8.8 e- Normal mode |
| Quantum Efficiency | > 55% @ 510nm (with micro lenses) |

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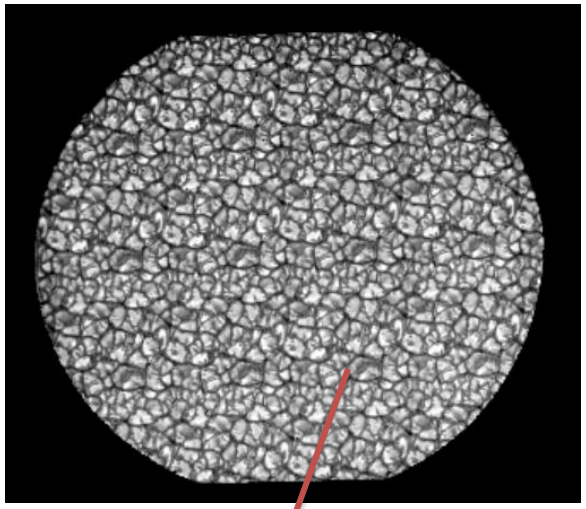
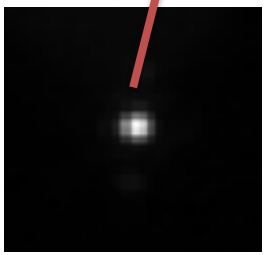
# Test-bed: Science Camera

Sun granulatio Image



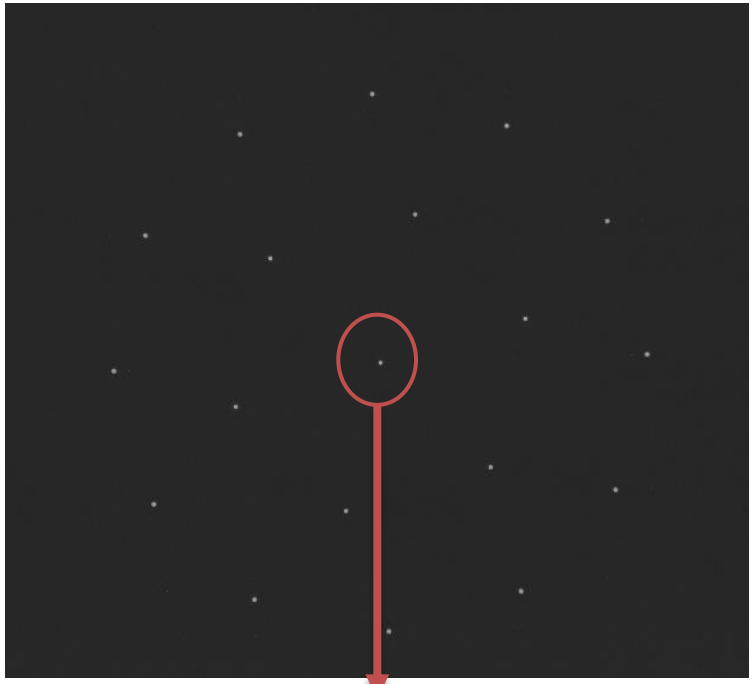
C = 21 %

PSF close loop SCAO
525nm±50nm SR ≈ 0.70

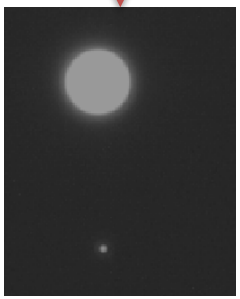


PSF fiber 532nm.
SR≈0.85

Pinholes Array



Ø: 0.4'' 150 µm



Ø: 0.026'' 10 µm

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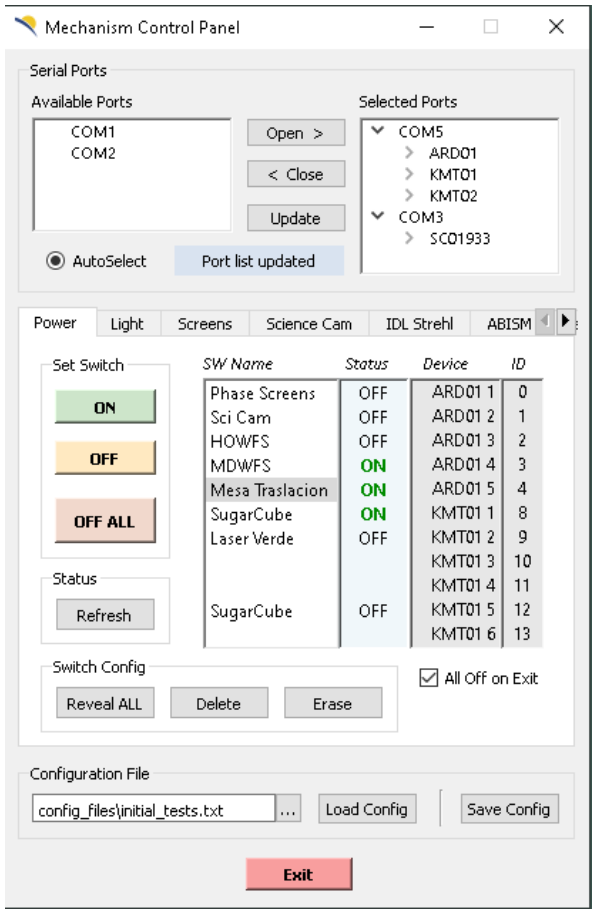
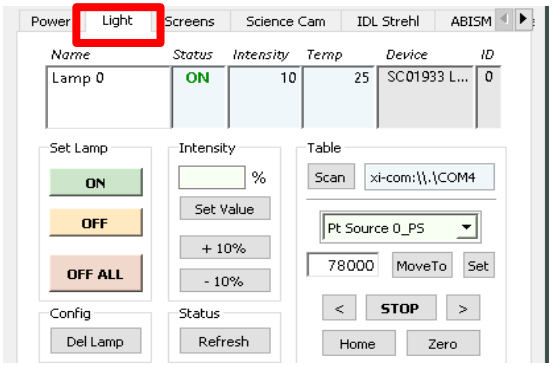
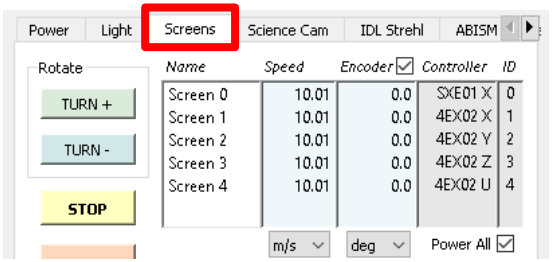
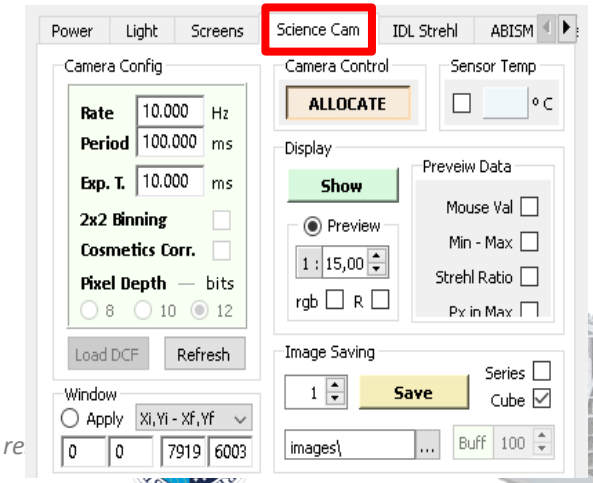
# Test-bed: Control software

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# AO Configurations

| | |
|---|---|
| **SCAO** | DM0 / HO-WFS |
| **GLAO1** | DM0 / HO-WFS & MD-WFS |
| **GLAO2** | DM0 / HO-MD-WFS |
| **MCAO 1** | DM0 / HO-WFS & DM1/MD-WFS |
| **MCAO 2** | DM0 / HO-WFS & DM1+DM2/MD-WFS |
| **MCAO 3** | DM0 +DM1/ HO-MD-WFS |
| **MCAO 4** | DM0 +DM1+DM2/ HO-MD-WFS |

*Control:*

DARC (RTC).

Frequency rate: 30Hz (limited by the WFS).

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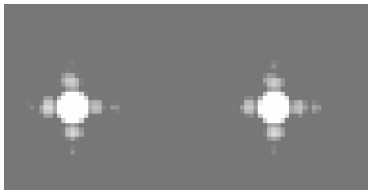
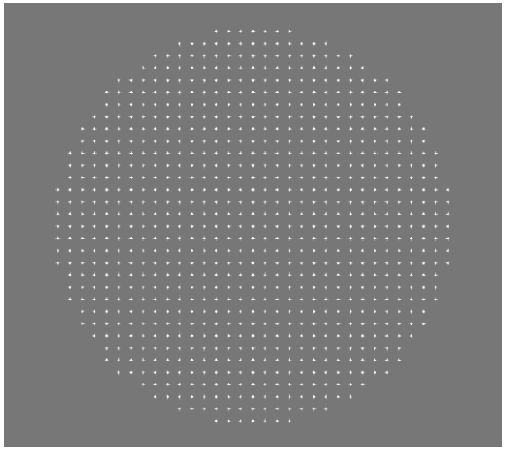
# Test-bed: HO WFS - SCAO

## Interaction matrix (pmx)

2 *zonal* alternatives:

- Basic poke.
- Sine poke.





2 *modal* alternatives:

- Zernike basic poke (819).
- KL basic poke (527 best).

## Reconstruction matrix (rmx)

Pseudo-inverse of the pmx by SVD.

- Zonal ('rcond' value).
- Modal ('rcond' value).

## Control strategy

- PI controller
- POLC

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# Test-bed: HO WFS - SCAO

## Evaluation of the results

WFS image:

- Temporal RMS of each centroid.
- Comparison of homogeneity.

Science image:

- Strehl ratio.
- FWHM in x and y axes.

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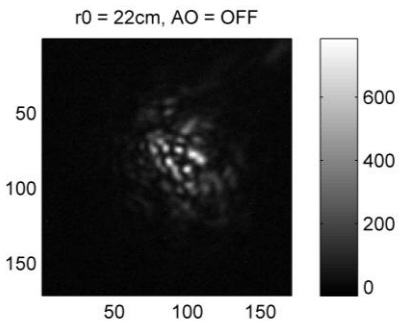
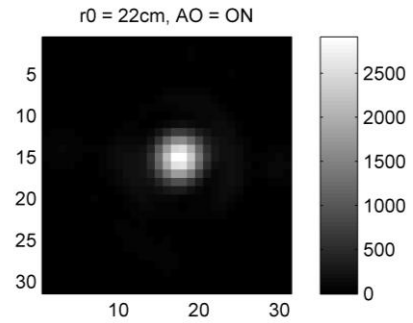
# Test-bed: HO WFS - SCAO

## $r_0 = 22cm$

*WFS image*

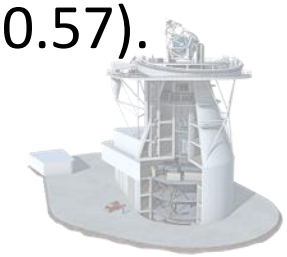
- Zonal slightly better than modal methods.
- Poke sine and regular zonal shows best performance.
- Zernike modes slightly better than KL.
- POLC seems not offering any advantage.




*Science image*

- Slighlty better results when using zonal approaches (regular, SR: 0.60).
- Zernike and KL reported very similar results (SR: 0.57).



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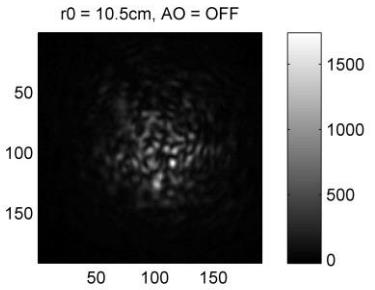
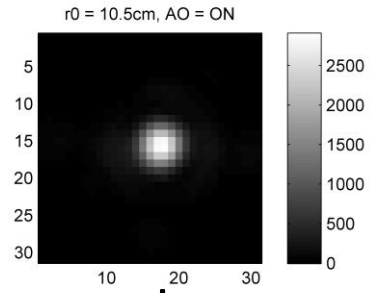
# Test-bed: HO WFS - SCAO

## $r_0$ = 10 cm

*WFS image*

- Similar conclusions can be drawn.
- Basic poke shows a poor performance.




*Science image*

- Slightly better results when using zonal approaches (poke sine, SR: 0.48).
- Zernike (SR:0.45) slightly better than KL (SR: 0.42 ).
- Degradation in basic poke performance (SR: 0.36).

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# Test-bed: HO WFS - SCAO

*J.Manuel Gonzalez et al SPIE 2022*

*"Laboratory results of SCAO: getting ready for the EST MCAO"*

- Zonal strategies outperformed the modal strategies in both scenarios.
- POLC seems to not have introduced any relevant benefit.
- Slight divergencies between SR and WFS could be due to:
  - Science image processing.
  - NCPA.
- Are we using the optimal tuning of each algorithm?

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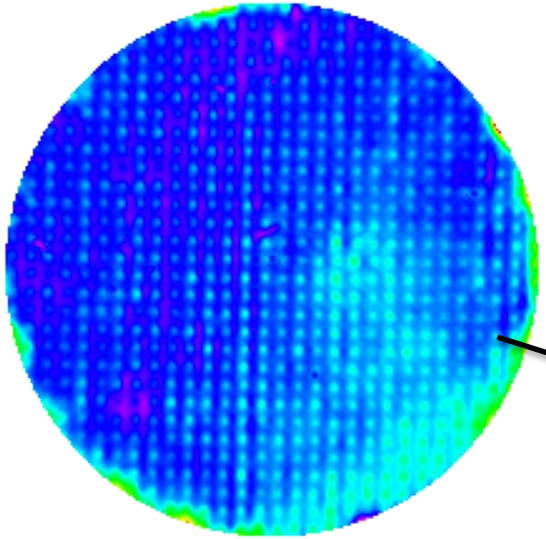
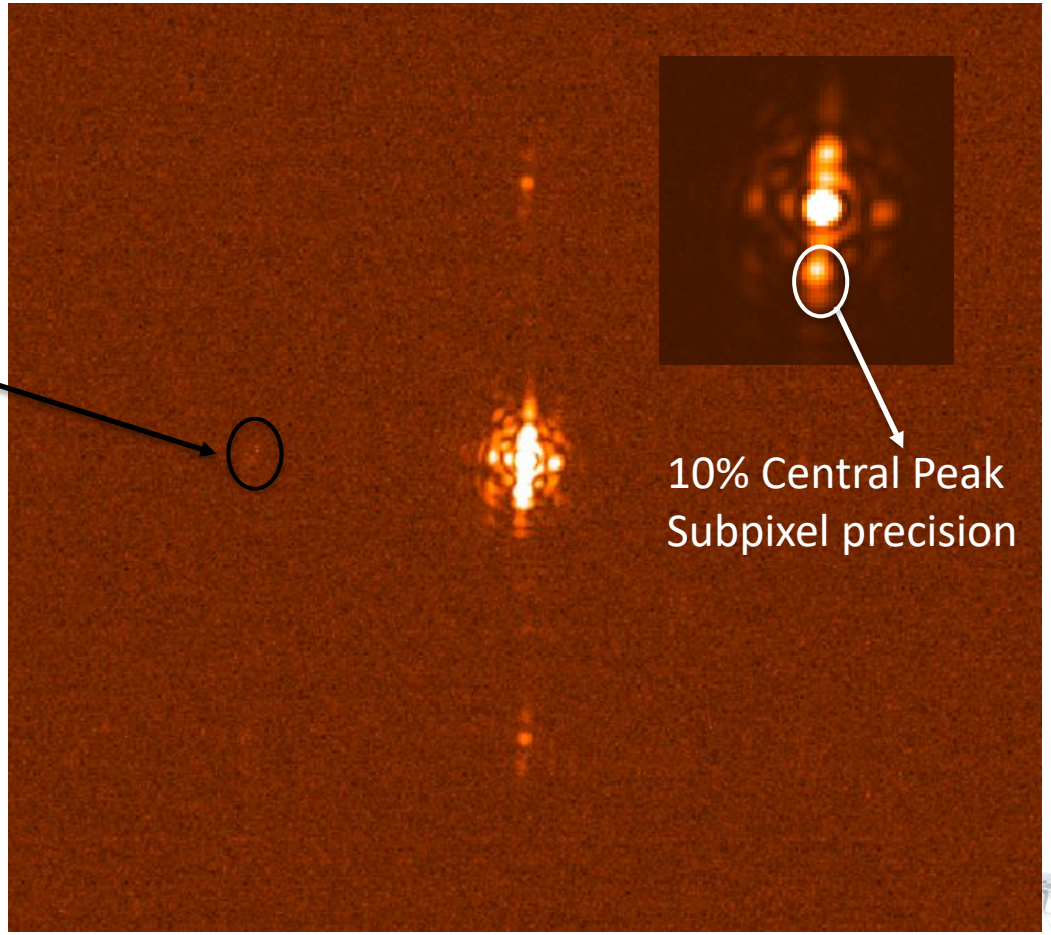
# Test-bed: HO WFS - SCAO

**Flatten DM**



**PSF**

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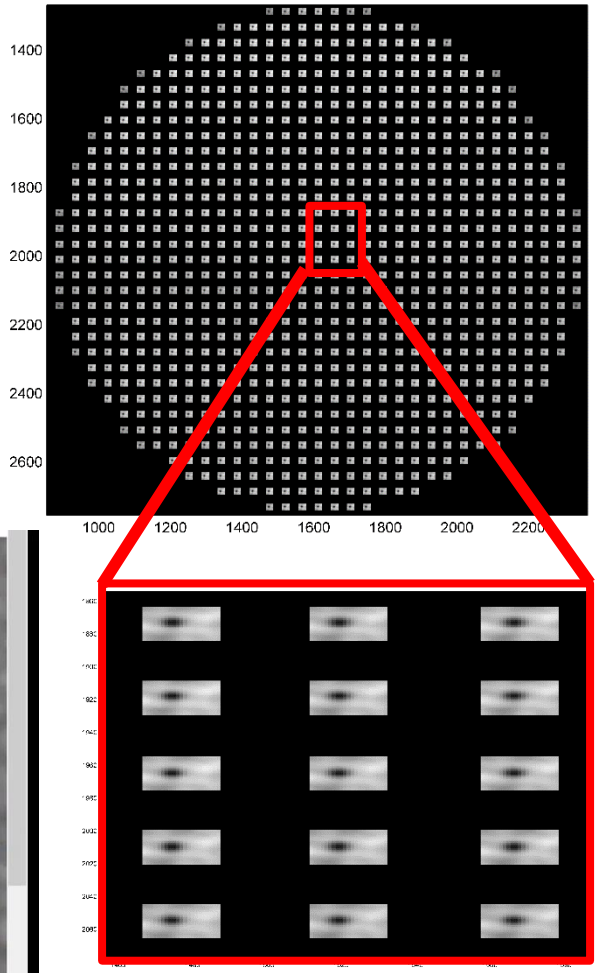
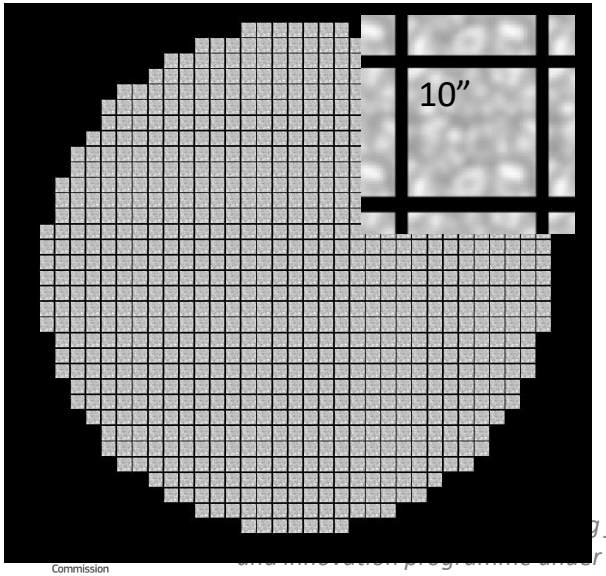
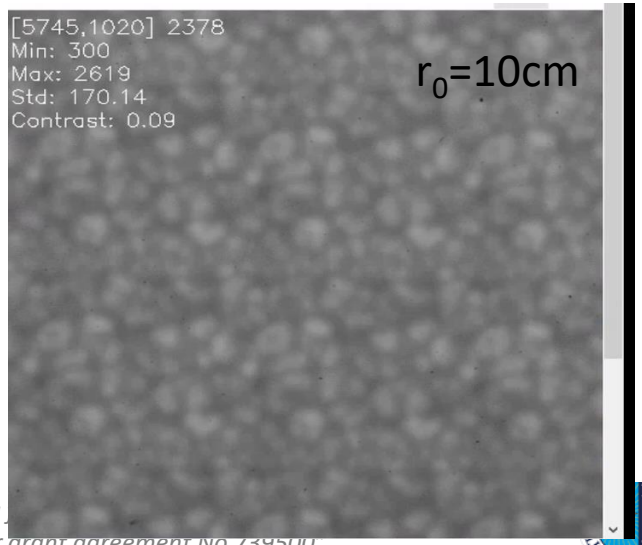
# Test-bed: HO WFS - SCAO

- Correlation image: Square difference.
- Sub-pixel precision: Parabolic fitting (3x3).
- Interaction matrix: Poke Sine method.
- Reconstruction matrix:

  Pseudoinverse matrix (SVD)
- Zonal control: PI controller.

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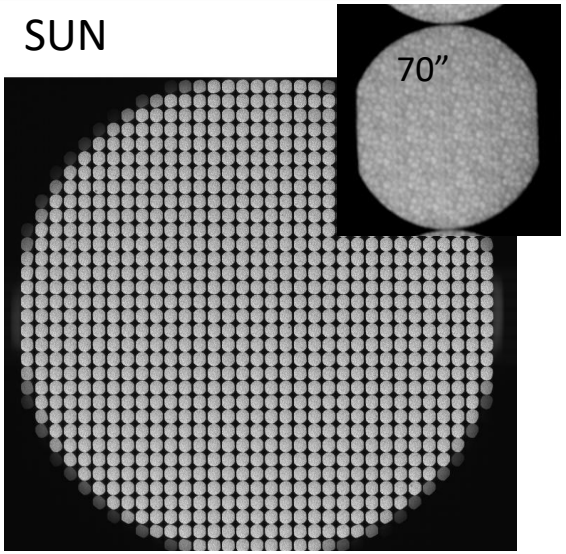
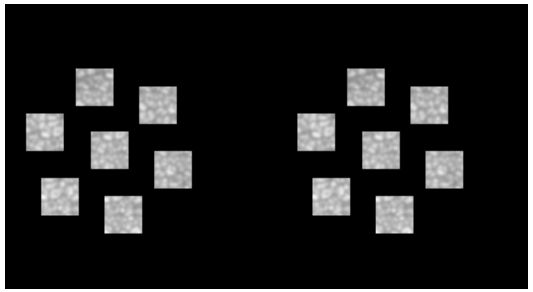
# Test-bed: HOMD WFS - GLAO

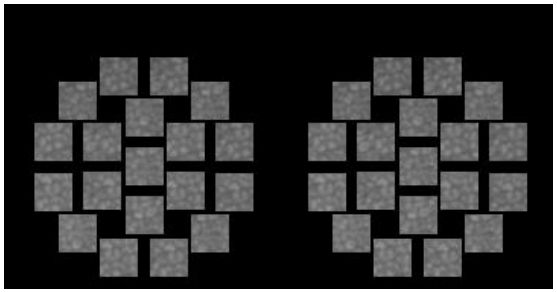
SUN



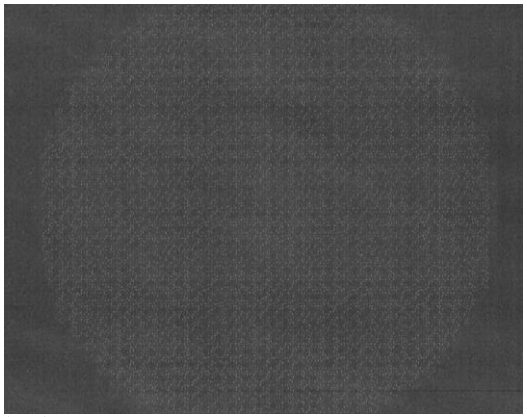

7 dir

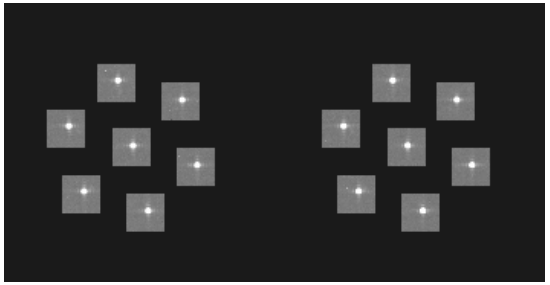


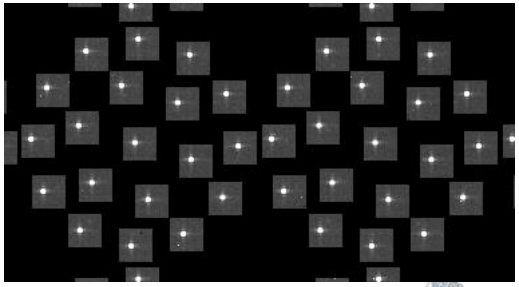
19 dir



Array Pinholes







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# Test-bed: HOMD WFS - GLAO

## Interaction matrix (pmx)

- Sine poke

## Reconstruction matrix (rmx)

Pseudo-inverse of the pmx by SVD.

- Zonal (‘rcond’ value).
- 7 directions

## Control:

- PI controller: adjusting decay factor and gain

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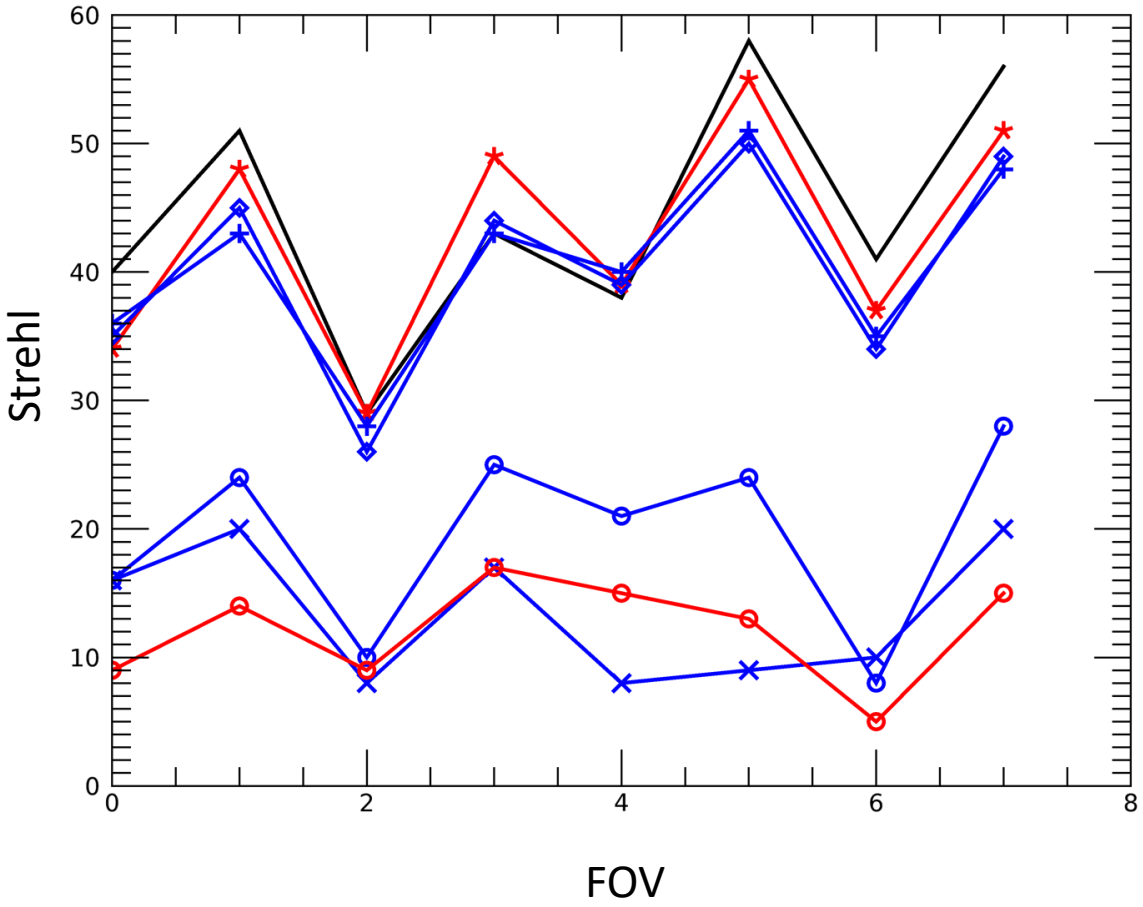
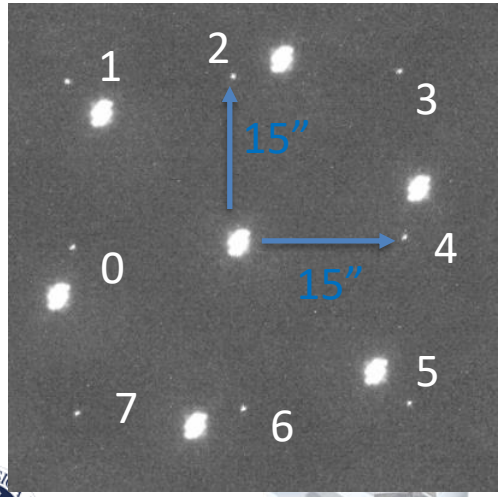
# Test-bed: HOMD WFS - GLAO




PSF
SCAO 10cm 0km
GLAO 10cm 0km 1dir
GLAO 10cm 0km 7dir
SCAO 30cm 4km
GLAO 30cm 4km
GLAO 30cm 10km

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# Perspectives

- Improve bench aligment to increase image quality.
- Improve correlation algorithms.
- Complete GLAO configurations:19 dirs, sun, MD-WFS.
- Implement MCAO with altitude DMs.

OBRIGADA !!!!!!

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