Getting to know the Pyramid wavefront sensor for high-order AO systems

Some recipes for performance improvement and risk mitigation

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Seminar at LAM, Nov. 29th 2018

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Introduction: ESO's Extremely Large Telescope, Adaptive Optics and the MICADO instrument

The ELT: An upcoming breakthrough in ground astronomy

ESO is building the largest telescope in the world at Cerro Armazones:
39 m primary mirror, 1 100 m^2 collecting surface, sub- 10 mas resolution

2006

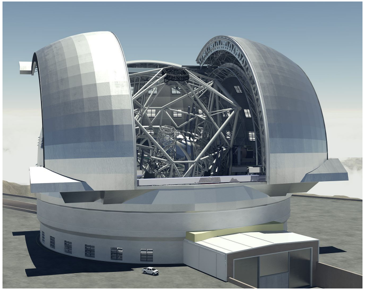
Contract signed

Budgeting 1 bn €

Call for instruments

2018

202n ($n = 4$)



20+ years of developments towards *Extremely Large science cases*:

Exoplanets - Black Holes - High z events - Extragalactic star pop. - Cosmology

The ELT: An upcoming breakthrough in ground astronomy

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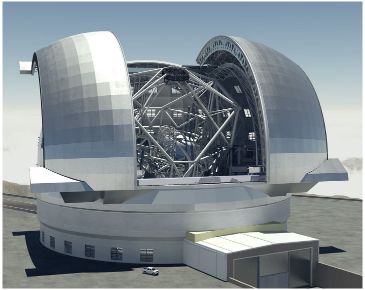
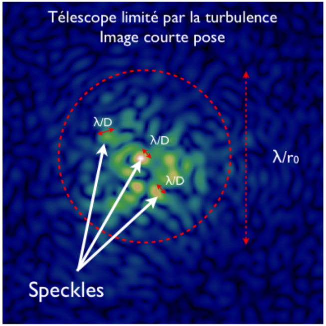


Working through *Extremely Large technological challenges*:

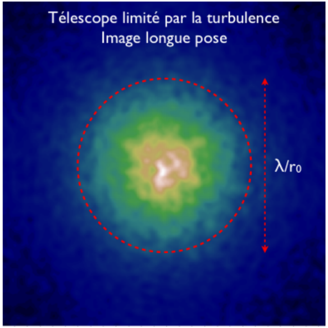
Segmented M1 (798 pieces) - 2.4 m adaptive M4 + M5 - New instruments; Everything scales up !

A quick AO recap: Why astronomers hate the atmosphere

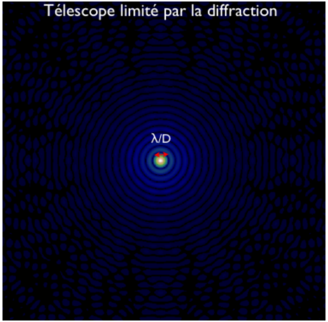
- Ground telescopes observe through the atmosphere.
- The atmosphere *ruins* image quality.



Short exposure: λ/D speckles in a λ/r_0 area.



Long exposure:
A big λ/r_0 spot.

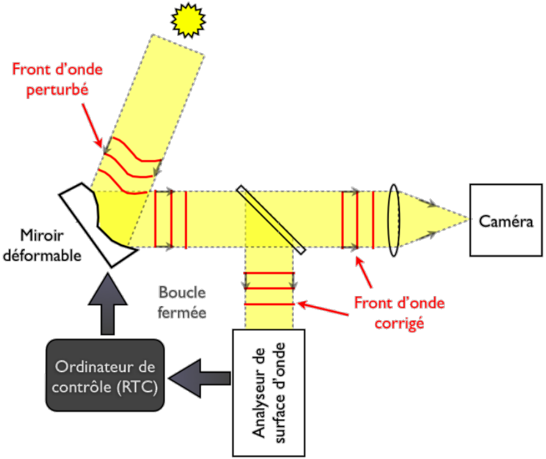


No atmosphere:
A sharp λ/D spot.

For the ELT in near infrared: separation power reduced by ≈ 200.
Atmosphere essentially makes the telescope useless!

A quick AO recap: How astronomers made telescopes useful again

Adaptive Optics: engineering-astronomy crossover for canceling atmospheric effects



Basic SCAO schematic (credits F. Vidal)

- Conceived in 50s (Babcock '53)
- First "On-sky" early 1980s
- First "Science grade" system in the 90s

AO systems scale quickly with tel. size

Engineering needs to follow up:

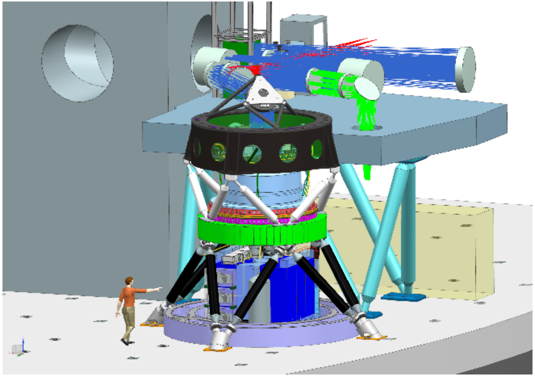
- RTCs (Optimizing soft and hard)
- DMs (Materials, surface, response)
- WFS (Concepts, optics, algorithms)

LESIA's involvement in the ELT: the MICADO SCAO system

MICADO - Multi AO Imaging Camera for Deep Observations

First light imager for the ELT

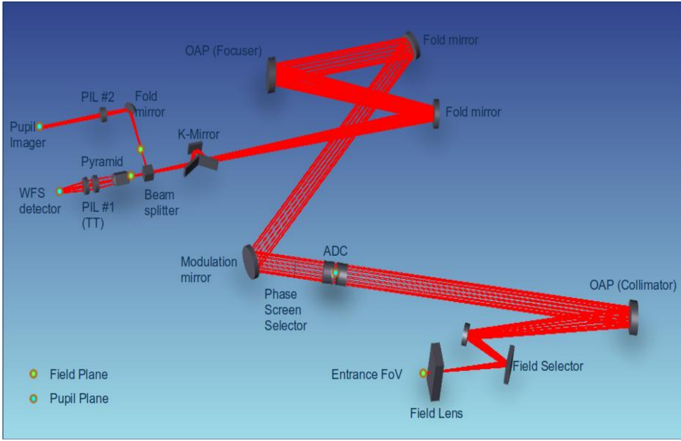
- Near IR (.8 - 2.4 μm)
- FOV 1 arcmin^2
- Astrometric imaging, spectroscopy, high-contrast coronagraphy
- 2 AO modes:
  - MOAO ← MAORY relay (wide field, high sky coverage)
  - SCAO ← LESIA AO team (top perf., reduced sky coverage)



SCAO WFS path design

Early on:

- the WFS is a critical subsystem
- Sensitivity & sky coverage requirements oblige to a PWFS



Current design of the SCAO WFS arm

SCAO WFS path design

Early on:

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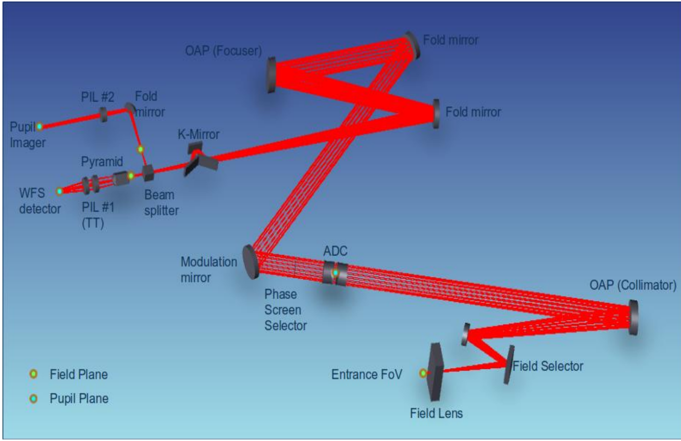
- Sensitivity & sky coverage requirements oblige to a PWFS

Therefore, the plan was to:

- Step up our wavefront sensing game
- Start Pyramid R&D
- *Hire PhD students*



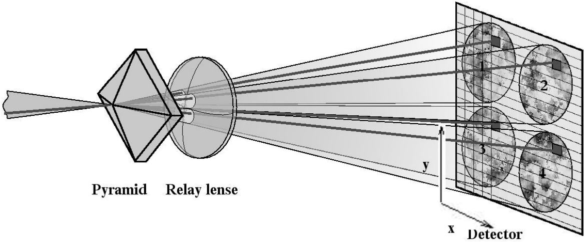
Current design of the SCAO WFS arm

The Pyramid Wavefront Sensor

The PWFS: A sensitivity-doping paradigm shift

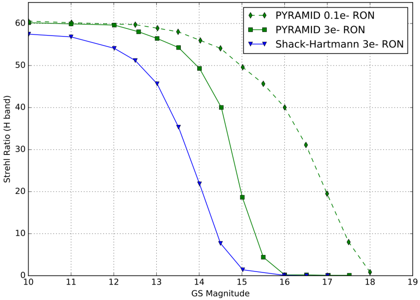
A wavefront sensor? An optical transform from phase to camera-readable information.
Yet, a good one is better !

Pyramid WFS (Ragazzoni, 1996)
LBT (2007) - 10 m upgrades - most ELT instruments



Pros: Sensitivity, versatility, less optics.
Cons: limited range, very nonlinear, NCPAs, ...

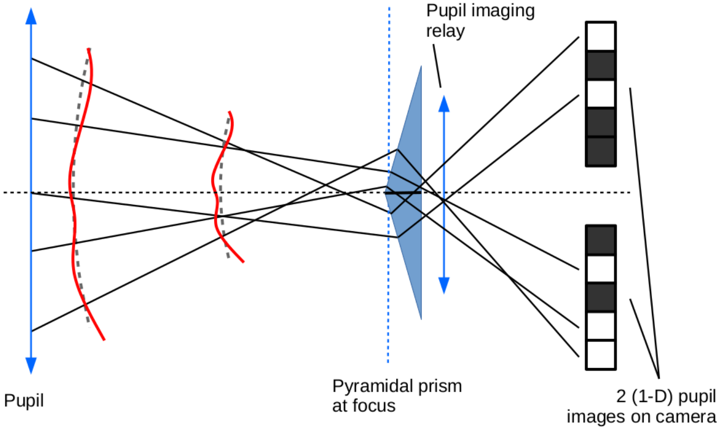
A sensitivity well beyond the SH:



Simulated SCAO Strehl vs. star magnitude (F. Vidal)

This sensitivity improvement (= coverage, = Strehl) is the sufficient argument to us:
WFS baseline = Pyramid.

The Pyramid with ray optics: phase-encoding pupil images



Wavefront error = *missing* the focus

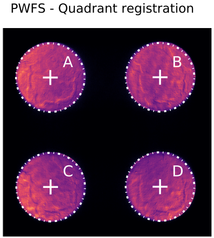
Rays above/below focus refracted in different pupil images

4 pupil images are formed.

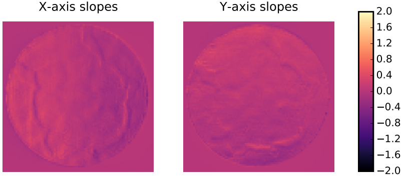
Pixel intensity depends on where the ray hits the prism.

→ intensity $\propto$ phase grad.

But what are *really* Pyramid signals ?



$$\begin{aligned} n &= < A+B+C+D >_{(x,y)} \\ \longrightarrow S_x &= \frac{A-B+C-D}{n}(x,y) \\ S_y &= \frac{A+B-C-D}{n}(x,y) \end{aligned} \quad \longrightarrow$$



S_x, S_y slopes map for the reference point.

Ragazzoni '96: Ray optics – Modulation-tuned gradient sensor with neat saturation.

Vérinaud '04: 1-D derivations – gradient or phase sensor across frequency range.

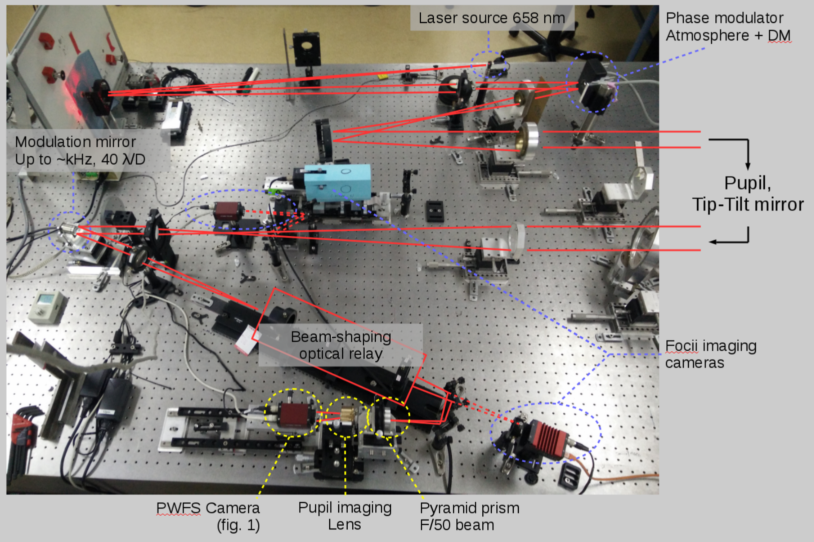
Fauvarque '16: The PWFS & $[S_x, S_y]$ have an OTF → Convolutional algos are OK ?

Need to investigate models, meaning, and critical points for ELT ops. E.g.:

Pixel misalignments → led to Deo et al., 2018
Handling variable sky conditions → my current research

A little detour: the PYRCADO testbed at LESIA

The PYRCADO testbed: A high order PWFS R&D setup



SLM in pupil plane:
Turbulence + virtual DM.

Pyramid WFS:
Up to 300 px. across pupil

Targeting high-speed, high-order AO.
For now: ≈ 5 Hz :'(

Versatile tool for design, test, integration, characterization, (etc) of soft & hardware.

PYRCADO testbed demo

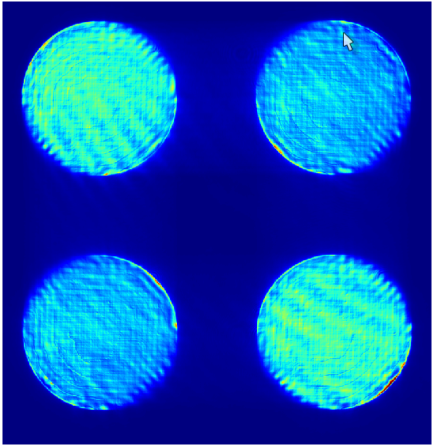
→ PYRCADO operating ←

My PhD research, Ep. 1:

Pyramid misalignments & prism defects

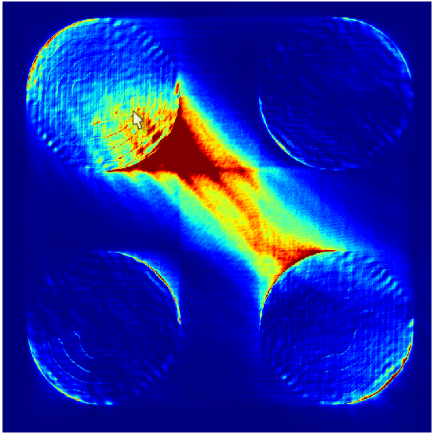
It all began with some little bench issues...

With modulation



So much wrong here !

Without modulation, right on the "*pin*"



How to fix it ? How to live with it ?

Misfabrications and misalignments

Many possible prism fabrication errors cause:

- Zero point quadrant flux variations
- Non-square quadrant layout

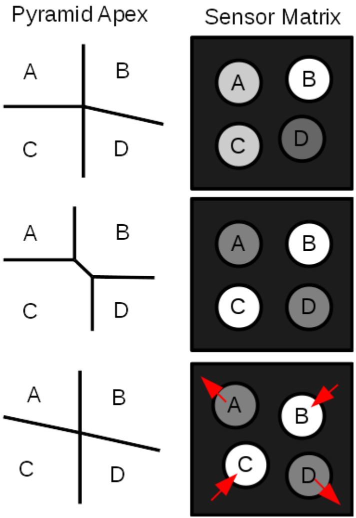
Theoretical *perfect* PWFS requires:

- Perfect rectangle layout
- Identical quadrant flux
- Integer pixel spacing between quadrants

A, B, C, D pixels must match exactly for PWFS validity.

How tight is specification: 1/10$^{\text{th}}$ pixel ?

Software quadrant fit and center select: 3/4 px. guaranteed.
Hardware accelerated processing: offset may be larger.
→ Impact study of free translations of all 4 quadrants.

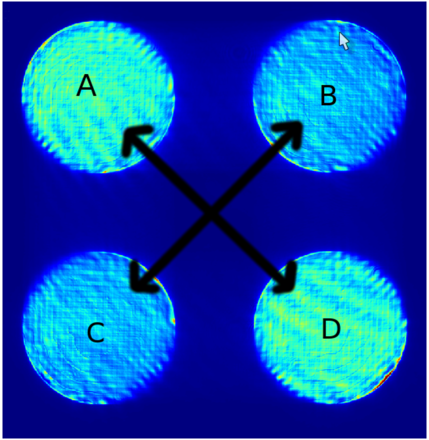


Expanded Space control: introducing some new slopes

Traditional gradient control slopes:

$$\begin{bmatrix} S_x \\ S_y \end{bmatrix}(x,y) = \begin{bmatrix} 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \end{bmatrix} \cdot \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}(x,y)$$

Why not use the cross term since symmetry is broken ?



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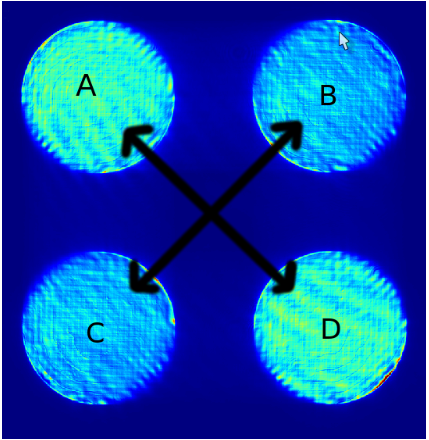
Why not use the cross term since symmetry is broken ?

Expanded slope space:

$$\begin{bmatrix} S_x \\ S_y \\ S_z \\ S_f \end{bmatrix}(x,y) = \underbrace{\begin{bmatrix} 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}}_{\mathbf{P}} \cdot \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}(x,y)$$



A misalignment test case - Comparing methods

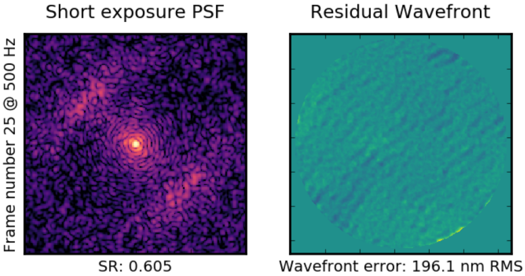
Misalignment test case:

$$x_A, y_A = -0.24, \ +0.46$$
$$x_B, y_B = +0.28, \ -0.49$$
$$x_C, y_C = -0.17, \ +0.38$$
$$x_D, y_D = +0.45, \ -0.47$$

- All offsets ≤ 0.5 pixels

For pupils of 55 px with 100 px separation, is equivalent to specs of:

- 2% tol. in refraction angle
- 12 mrad rotation of the prism



With $[S_x, \ S_y]$:
a portion of the correction zone is lost.

A misalignment test case - Comparing methods

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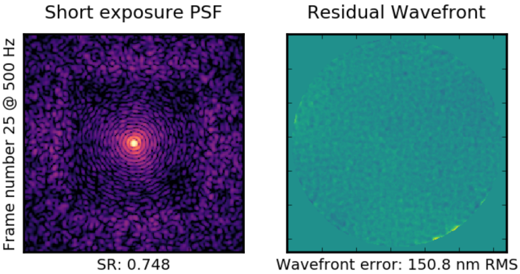
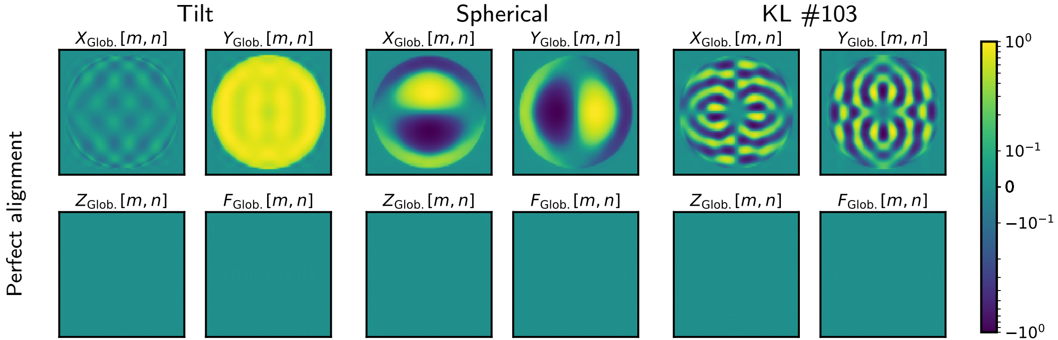


With $[S_x,\ S_y,\ S_z,\ S_f]$:

Full correction is achieved !

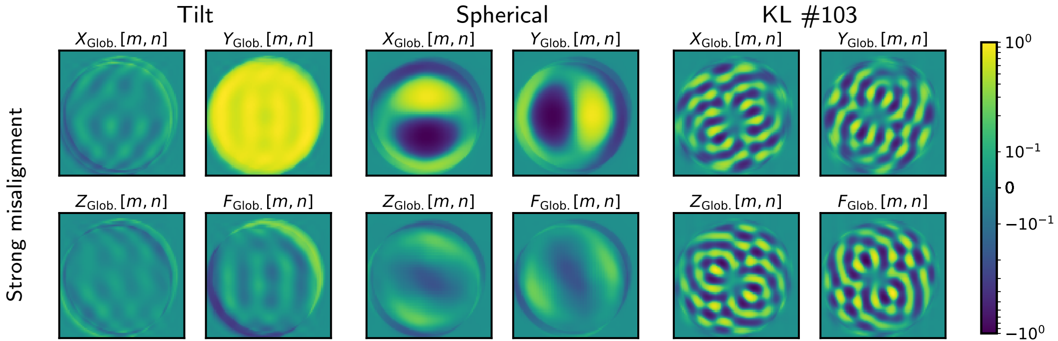
A misalignment test case - the interaction matrix

1 - Perfectly aligned PWFS: S_z, S_f void of information



A misalignment test case - the interaction matrix

2 - Misaligned case: S_z, S_f as critical as S_x, S_y



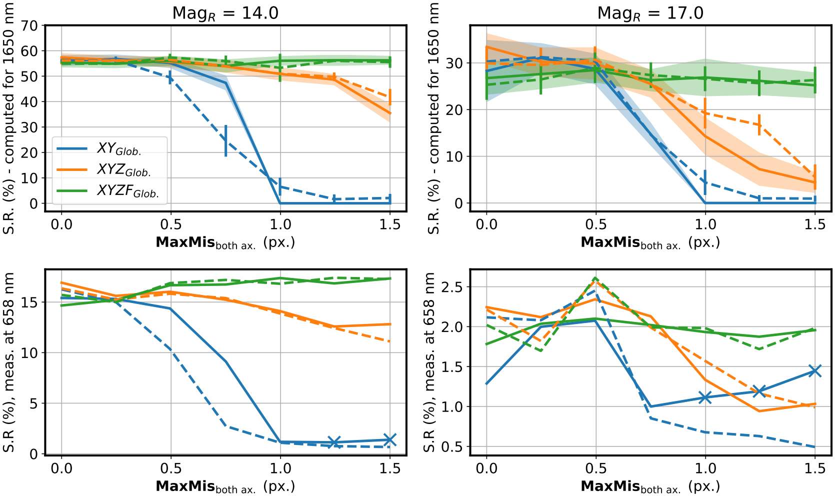
Validating on the bench: performance of $[S_x, \ S_y, \ S_z, \ S_f]$ control

18 m telescope

39×39 DM (SLM)

46×46 px. PWFS
Sensing at 658 nm

$r_{\text{Mod}} = 6\lambda/D$



Upon this: generalizing the misalignment and ESC approach

We conducted a detailed analysis of what the misalignment does to the useful information to retrieve the phase (the *original* S_x, S_y)

- For a perfect alignment, the phase information is completely in S_x & S_y
- Yet with summit defect / misalignment, this info is spread in all 4 terms
- Using all 4 S_x, S_y, S_z, S_f is equivalent to having a perfect PWFS regardless of the alignment.

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And in conclusion of this study:

- We will need twice the RTC computing power to use all 4 slopes maps
- We can skip the **P** transform altogether and feed all illuminated pixels to the RTC
- Yet, the SNR is unaffected: same number of pixels read, identical noise propagation
- We can relax the specs of the prism design a lot: 0.1 px.$\rightarrow$0.5 px. or even more.

  CCD pupil positioning is not a first order design constraint anymore.

Episode 2:

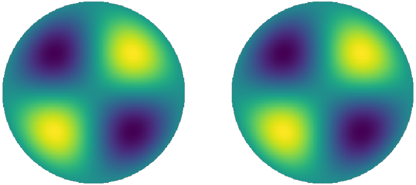
A critical nonlinearity issue: Optical Gain
Modelization and numerical investigations

Nonlinearities: the Optical Gain (OG)

Loss of sensitivity between calibration/operation
During operation, PWFS sees a lot less signal
depends on system, r_{Mod}, atmospheric conditions

Critical to understand and compensate:

- Getting some/more performance in bad seeing
- Using the pyramid with NCPAs



ϕ
Mode shown
10.0 nm RMS

$\phi^\star$
Mode reconstructed
10.0 nm RMS

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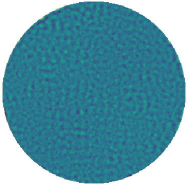
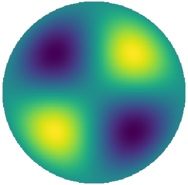


ϕ_{Ref}
Fitting residual
129 nm RMS



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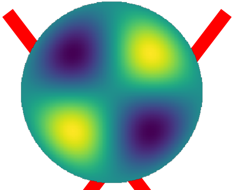

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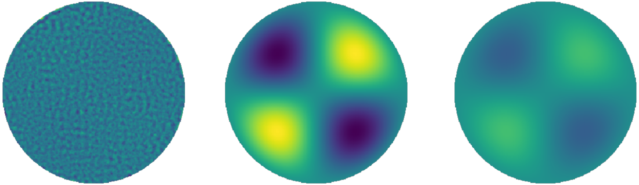

ϕ_{Ref}
Fitting residual
129 nm RMS

ϕ
Mode shown
10.0 nm RMS

$\phi^{\star} \approx G_{||} \times \phi$
Mode reconstructed
4.0 nm RMS

Astigmatism signal 60 % lower due to operating conditions !

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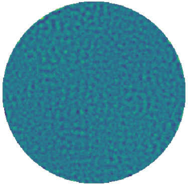

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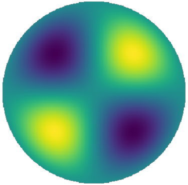

ϕ
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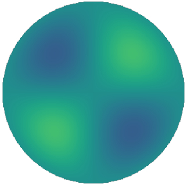

$\phi^\star \approx G_{||} \times \phi$
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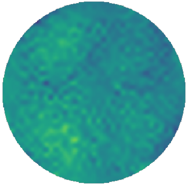

$\phi^\star_\perp$
Undue reconstruction
0.5 nm RMS

Astigmatism signal 60 % lower due to operating conditions !
Parasite signal of 5 % added on top !

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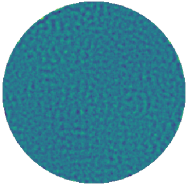

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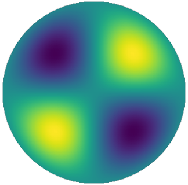

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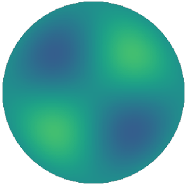

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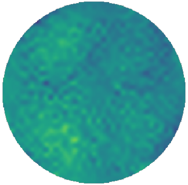

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Increase the controller gain by 2.5 ?

Optical Gain Modal Compensation (OGMC) - Objective of the approach

Using the KL basis of the DM $\mathrm{KL}_1 \ldots \mathrm{KL}_N$

Find compensation coefficients $G_{\mathrm{opt}}(\mathrm{KL}_i)$.
(dep. on the WFS state, atmos. conditions, ...)

Rec: flat-phase modal command matrix

Update **Rec** with:

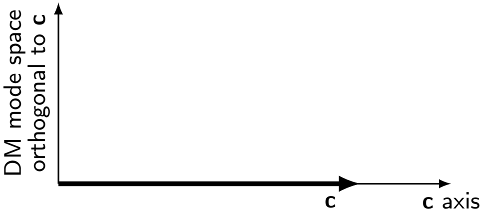
$$\textbf{Rec}[\mathrm{OGMC}] = \begin{bmatrix} G_{\mathrm{opt}}(\mathrm{KL}_1) & & 0 \\ & \ddots & \\ 0 & & G_{\mathrm{opt}}(\mathrm{KL}_N) \end{bmatrix} \cdot \textbf{Rec}$$

→ Each mode of basis compensated appropriately

Problem solved ?
How to get the G_{opt}?

Reconstruction with optical gain - DM space analysis

Let **c** be a DM mode



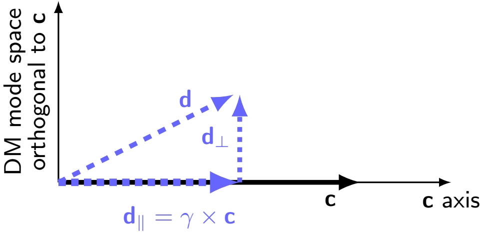
Reconstruction with optical gain - DM space analysis

Let **c** be a DM mode

Some phase residual + push-pull of $\pm\mathbf{c}$:
PWFS reconstructs $\mathbf{d} \neq \mathbf{c}$

Colinear component $\mathbf{d}_{||} = \gamma \times \mathbf{c}$
γ: sensitivity loss factor

Disturbing component $\mathbf{d}_{\perp}$



Reconstruction with optical gain - DM space analysis

Let **c** be a DM mode

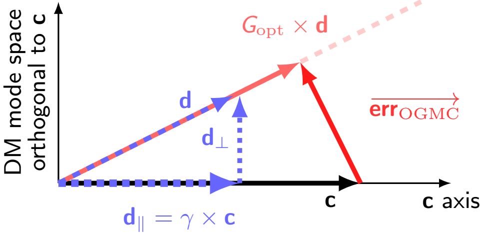
Some phase residual + push-pull of $\pm\mathbf{c}$:
PWFS reconstructs $\mathbf{d} \neq \mathbf{c}$

Colinear component $\mathbf{d}_{||} = \gamma \times \mathbf{c}$
γ: sensitivity loss factor

Disturbing component $\mathbf{d}_{\perp}$

Good rescaling for ϕ around ϕ_{ref}:

G_{opt} such that $\overrightarrow{\mathbf{err}_{\text{OGMC}}}$ is minimal



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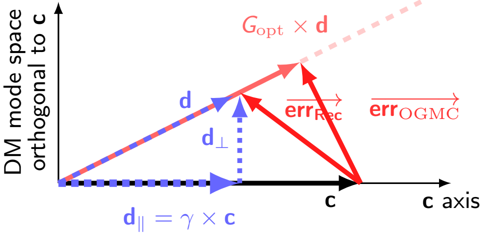


Quantities to analyse:

Error without OGMC: $\mathrm{E}_{\mathrm{Rec}}$
Error after OGMC: $\mathrm{E}_{\mathrm{OGMC}}$

- both dimensionless, in units of $||\mathbf{c}||$ -

OGMC $\equiv$ Optical Gain Modal Compensation

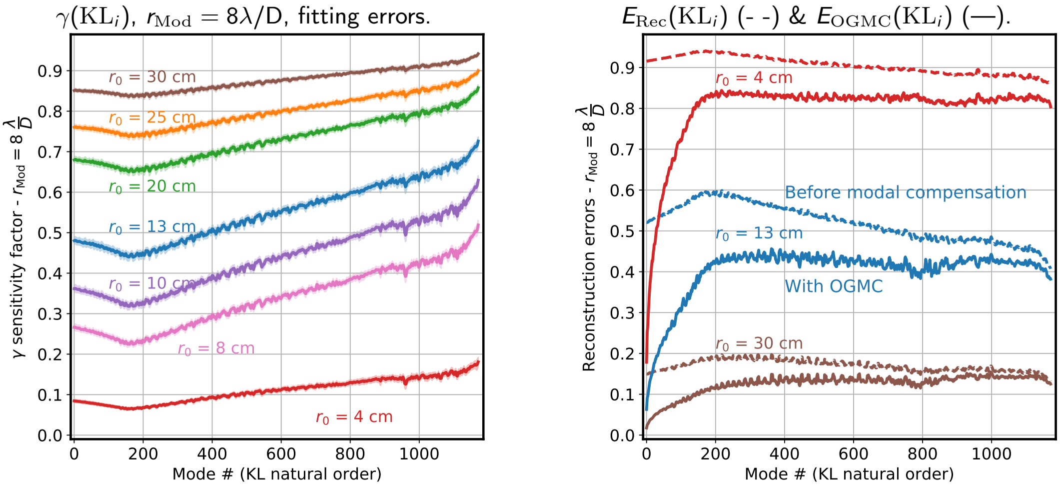
Simulation parameters

Numerical simulations configuration

Telescope	D = 18.0 m diameter
Turbulence layer	Single Von-Karmann GL Selectable r_0 – $L_0 = 25$ m
Source	On-axis natural guide star
Loop rate	500 Hz (200 Hz)
DM	39×39 pitch = 47 cm 1,177 KL modes
Subap.	61×61
Measurements	all illuminated pixels
λ_{PWFS}	658 nm
PWFS modulation	Circular; selectable r_{Mod}.
Noise	0.3 e^{-}
Controller	Modal integrator 2 frames latency
$\lambda_{\mathrm{Science}}$	1,650 nm

Note: all r_0 in this talk given at 500 nm.

Modal coefficients - Reconstruction error



γ - depends only on r_0 - less than 3% variation with turbulence realization.

$E_{\mathrm{Rec}} \longrightarrow E_{\mathrm{OGMC}}$ - Dramatic nonlinearity error reduction for low & mid orders.

End-to-end OGMC comparative performance – for static and known r_0

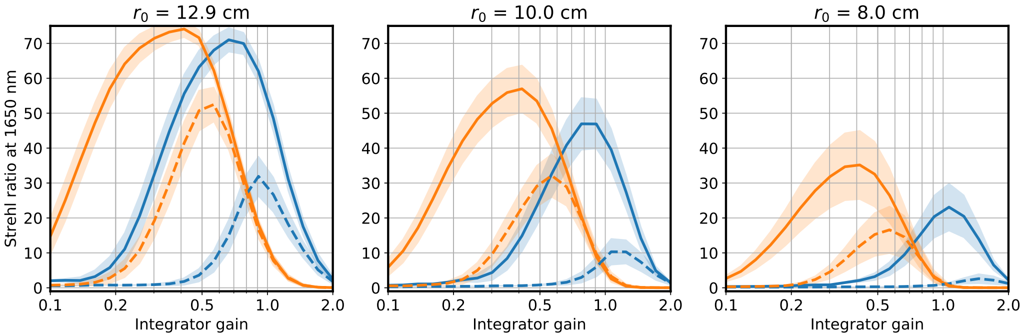
Eliminate loop gain contribution
What does OGMC bring on top of it ?

Finding out with simulations
Loop gain sweep: 0.1 – 2.0,
$r_{\mathrm{Mod}} = 4\lambda/D$

Without noise:

Top H-band Strehl performance

r_0	12.9 cm	10.0 cm	8.0 cm
—— Scalar (500Hz)	71	47	23
—— OGMC (500Hz)	74	57	35
- - - Scalar (200Hz)	32	10	3
- - - OGMC (200Hz)	52	32	17



End-to-end OGMC comparative performance – for static and known r_0

Eliminate loop gain contribution
What does OGMC bring on top of it ?

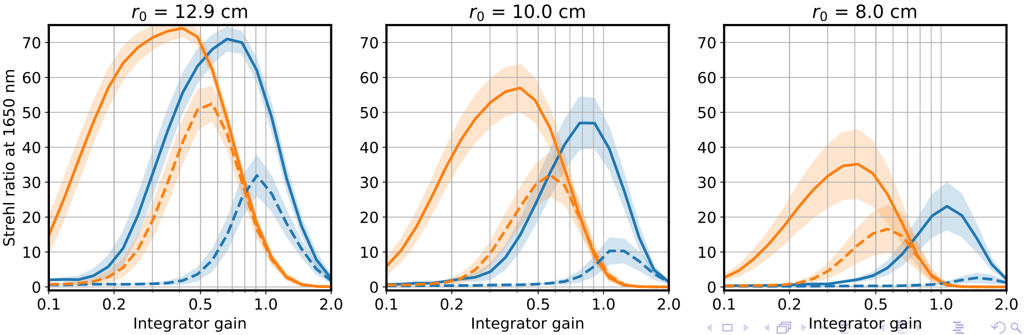
Finding out with simulations
Loop gain sweep: 0.1 – 2.0,
$r_{\mathrm{Mod}} = 4\lambda/D$

Without noise:

- Performance is always increased
- Gain at best S.R. is stable at 0.4.
- Most gain for bright stars in poor seeing
  → expected increase of useful tel. time

But:

- We knew the seeing & it never changed

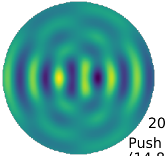


Episode 3:

A method for on-sky operations:
Poking some modes for automatic compensation updates

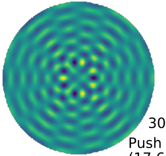
Mirror poking and PWFS frequency-locked detection – $r_{\mathrm{Mod}} = 8\lambda/D$, $\mathrm{Mag}_{\mathrm{R}} = 16$, $r_0 = 13$ cm

KL #82



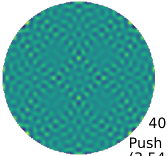
20 Hz
Push 42.0 nm P-P
(14.86 nm RMS)

KL #394

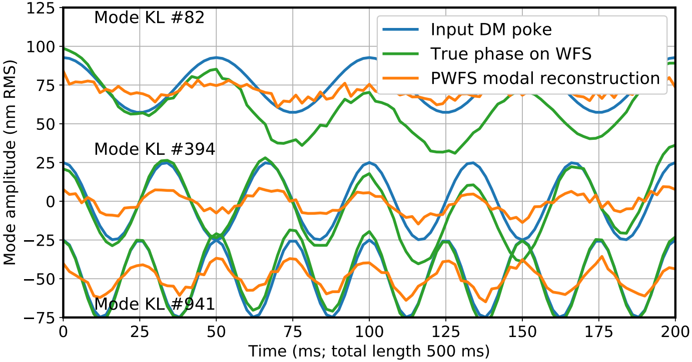


30 Hz
Push 50.0 nm P-P
(17.68 nm RMS)

KL #941



40 Hz
Push 10.0 nm P-P
(3.54 nm RMS)

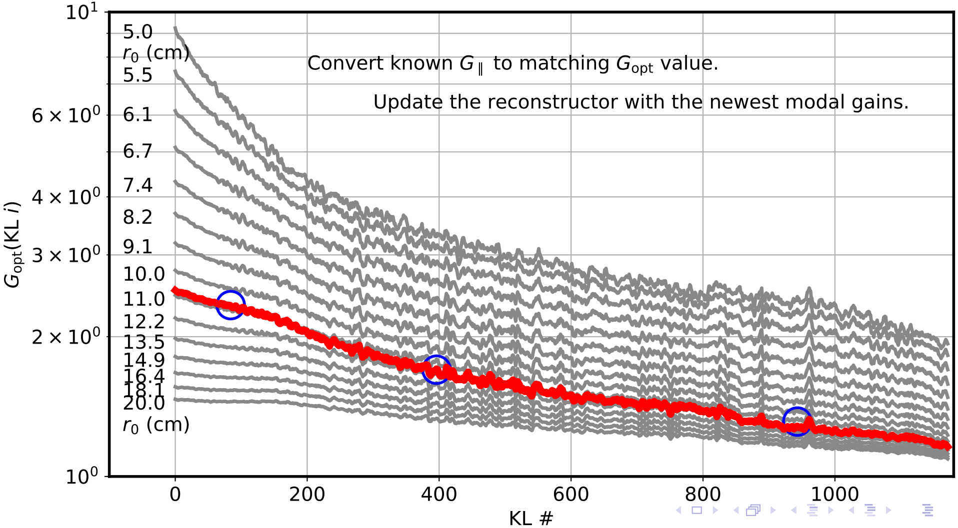


- Sinusoidal excitation of 3 modes. Controller is released.
- Temporal frequencies - 20 Hz to 40 Hz ; duration 0.5 s.
- Push amplitudes automatically detected with ad-hoc SNR measurement – total disturbance 10-30 nm RMS (here 23nm).
- Collect amplitude in PWFS output: measure $\gamma(\mathrm{KL}_i)$
  Convert: $G_{\mathrm{opt}}(\#82) = 2.4$, $G_{\mathrm{opt}}(\#394) = 1.7$, $G_{\mathrm{opt}}(\#941) = 1.3$

Abaqus interpolation - Measuring all modes

Still $r_{\mathrm{Mod}} = 8\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$, $r_0 = 12.9$ cm

Abaqus obtained from numerical simulations once. At most 1-2 d. calculations for ELT model.

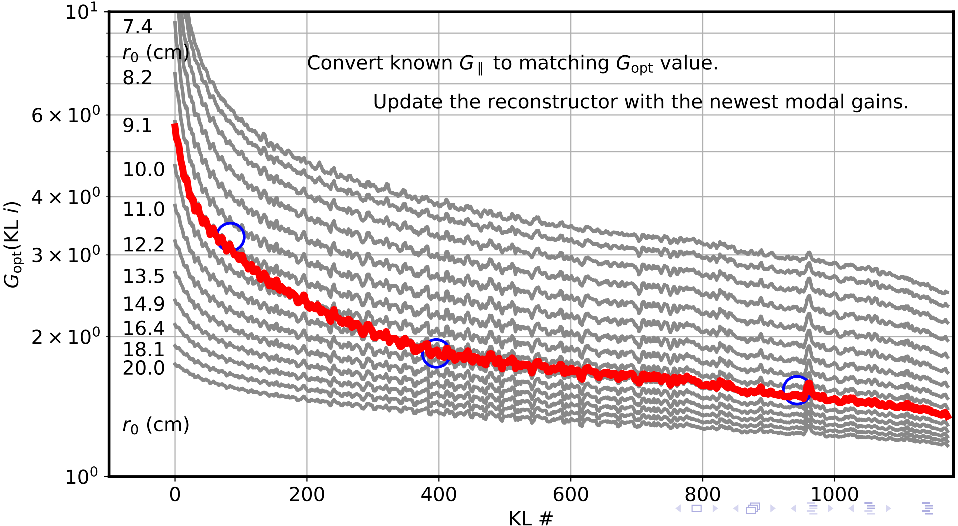


Convert known $G_{\parallel}$ to matching G_{opt} value.

Update the reconstructor with the newest modal gains.

Abaqus interpolation - Measuring all modes

Another example: $r_{\mathrm{Mod}} = 2\frac{\lambda}{D}$, $\mathrm{Mag_R} = 16$, $r_0 = 12.9$ cm

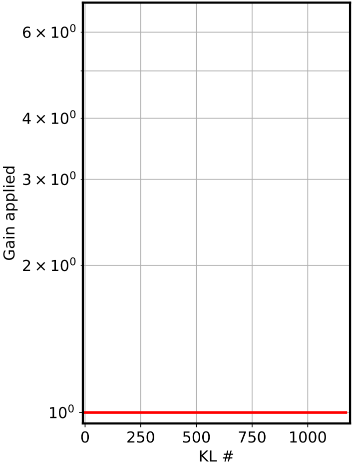


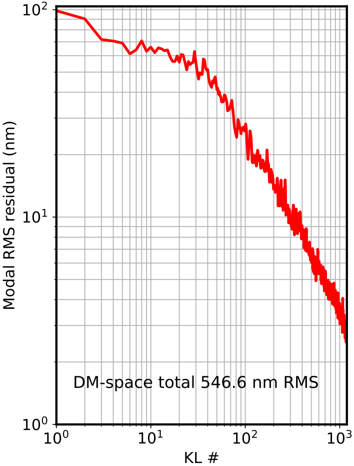
Convert known $G_\parallel$ to matching G_{opt} value.

Update the reconstructor with the newest modal gains.

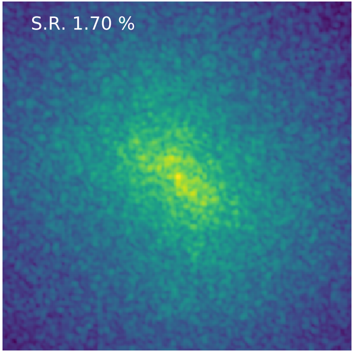
Bootstrapping without knowledge of atmospheric conditions

$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Step 0: set all OGMC coefficients to 1., set integrator gain to bandwidth-optimal 0.4



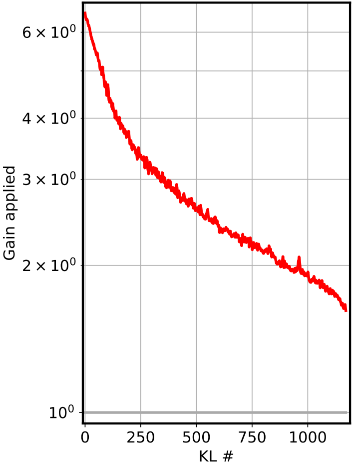


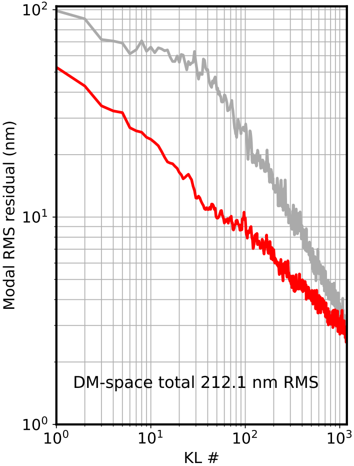
3 second H-band PSF



Bootstrapping without knowledge of atmospheric conditions

$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Step 1: After 1 pass of mode poking for .5 sec





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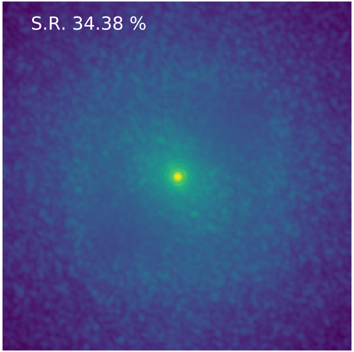
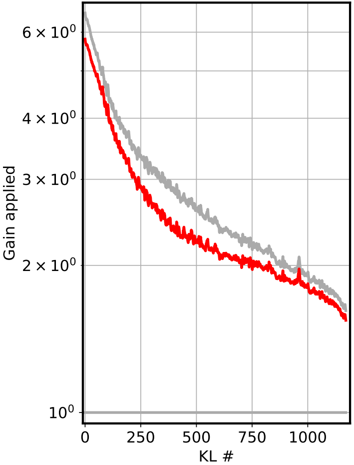
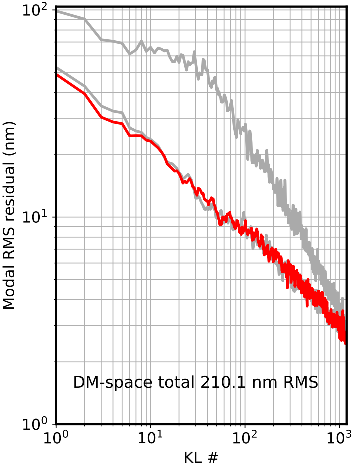


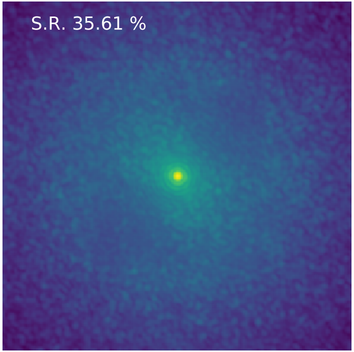
Bootstrapping without knowledge of atmospheric conditions

$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Step 2: After 2 passes.



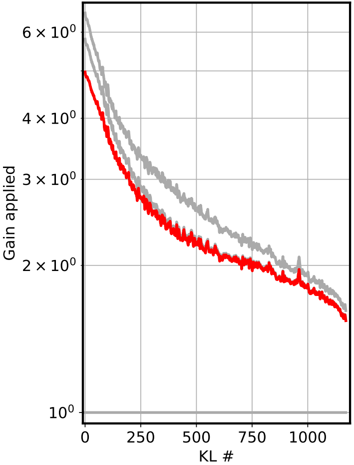


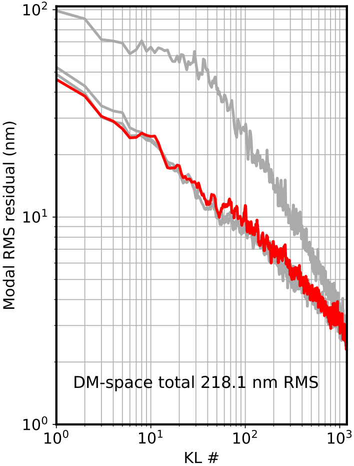
3 second H-band PSF



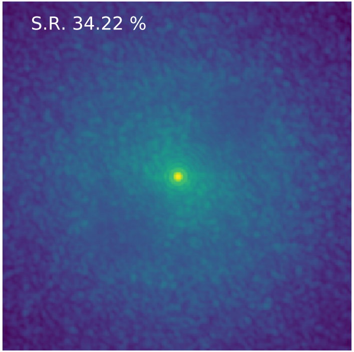
Bootstrapping without knowledge of atmospheric conditions

$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Step 3: After 3 passes. Bootstrap is stable and completed



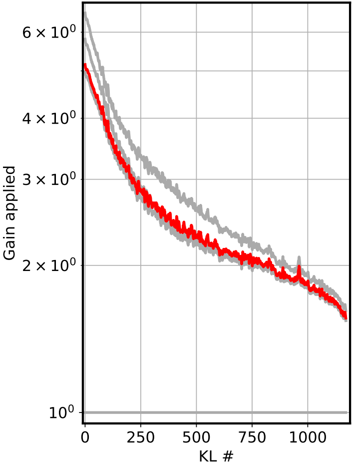


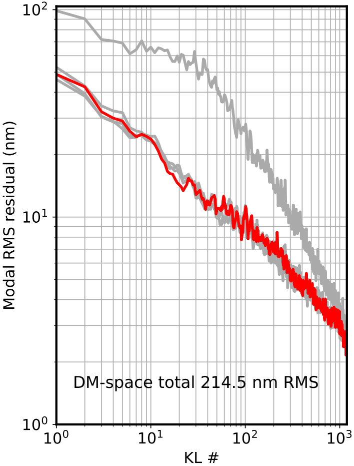
3 second H-band PSF



Bootstrapping without knowledge of atmospheric conditions

$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Much later: after 50 passes, randomly resetting the atmosphere each time.





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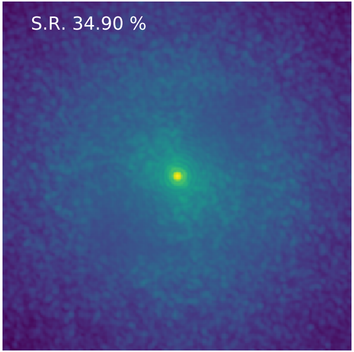
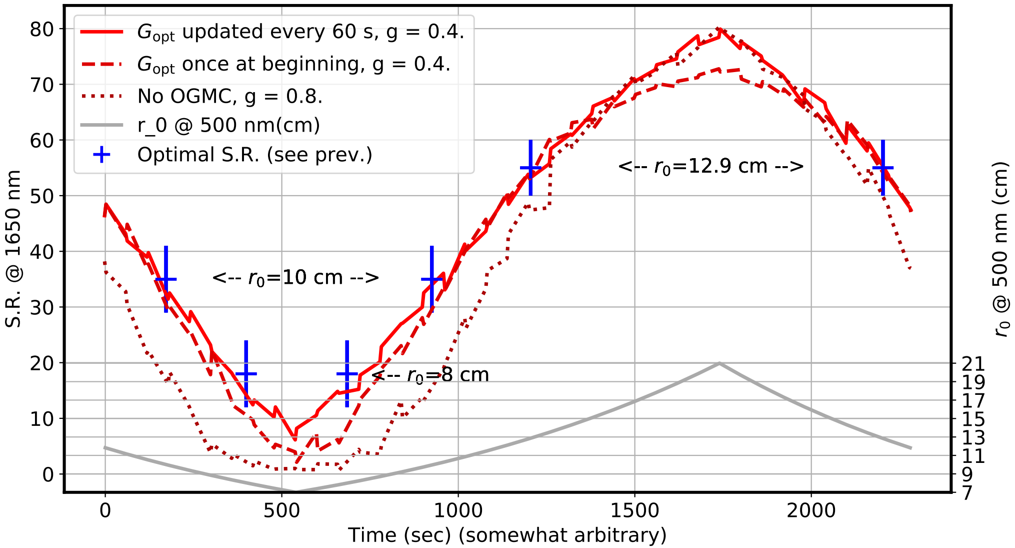


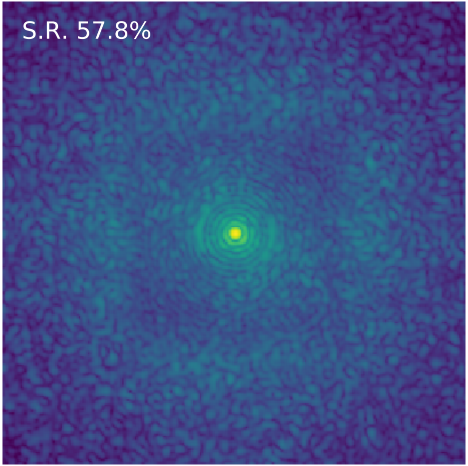
When r_0 varies wildly/widely: poke & update every minute for 6% r_0 variation steps



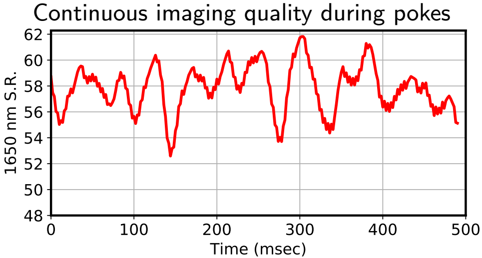
Performance during the poking cycle

Bright star - r_0= 10 cm

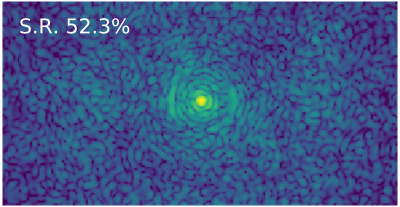
LE PSF across 500 msec. poke cycle



Nominal LE SR: 55±3%


Continuous imaging quality during pokes

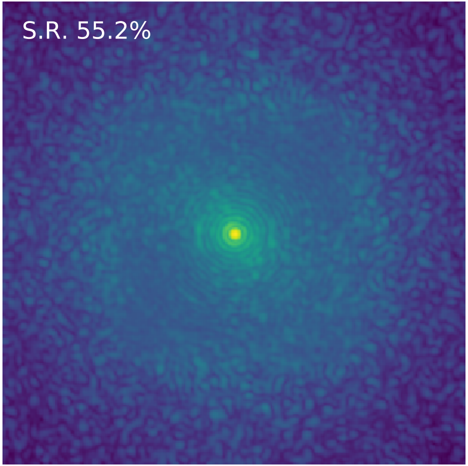
Worst 10 msec PSF



Performance during the poking cycle

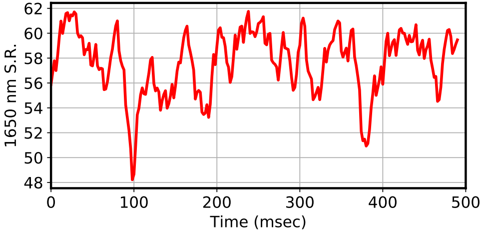
Mag_R = 16 - r_0= 12.9 cm

LE PSF across 500 msec. poke cycle

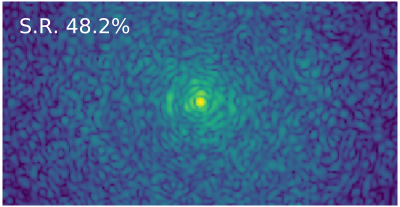


Nominal LE SR: 54±4%

Continuous imaging quality during pokes



Worst 10 msec PSF



Optical gain and the tracking method: summary

On optical gain:

- Small signal component of nonlinearity
- KL basis a fitting candidate for this model

On the OGMC method:

- Large reduction of nonlin. error for low orders
- Valuable increase in end-to-end perf.

On the poking method:

- Performance comparable to when r_0 is known/static
- Stable across very long durations & large seeing changes
- Little interference with science

Next up: integrate the algorithm into the MICADO RTC prototype
    Upgrade simulations to ELT-sized problems
    Run complete batches on PYRCADO
And: investigate better/other models non-small signal nonlinearity !

Perspectives

CANARDO: Going on-sky

Objectives:

- Validating all our recipes, algorithms, calibrations on sky
- Validating the expected performance of the –almost– complete MICADO SCAO WFS+RTC
- Being exposed to real, changing conditions which were not conceived in the lab.

Set up:

- Leveraging existing CANARY bench at William Herschel Telescope (4.2 m, Canary Islands)
- Using Engineering models of WFS and RTC
- R&D DM – ALPAO 64×64

Target: On-sky 2021

An ELT SCAO on a 4.2 m: **serious** performance is expected

I hope these Pyramid recipes gave you some appetite for more!