A Modal Approach to Optical Gain Compensation for the PWFS

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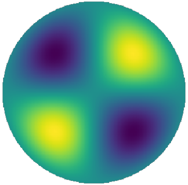
The Optical Gain phenomenon

Nonlinearities: the Optical Gain (OG)

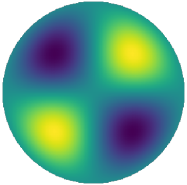
Loss of sensitivity between calibration/operation
During operation, PWFS sees a lot less signal
depends on system, r_{Mod}, atmospheric conditions

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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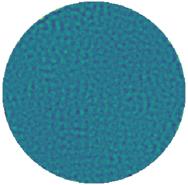
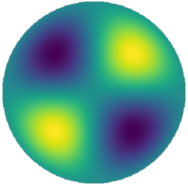
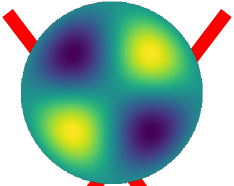


ϕ_{Ref}
Fitting residual
129 nm RMS



ϕ
Mode shown
10.0 nm RMS



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

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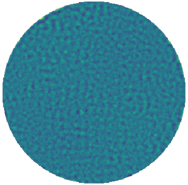

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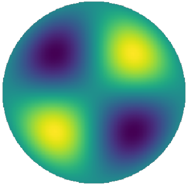
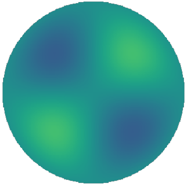


ϕ
Mode shown
10.0 nm RMS



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

Astigmatism signal 60 % lower due to operating conditions !

Nonlinearities: the Optical Gain (OG)

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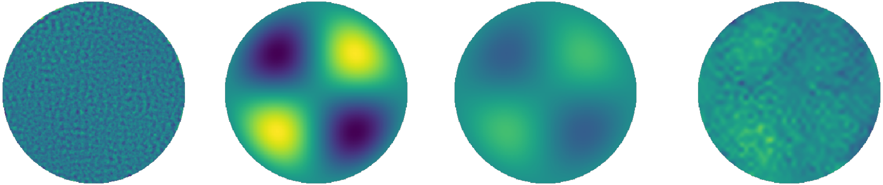

ϕ_{Ref}	ϕ	$\phi^{\star} \approx G_{\parallel} \times \phi$	$\phi^{\star}_{\perp}$
Fitting residual	Mode shown	Mode reconstructed	Undue reconstruction
129 nm RMS	10.0 nm RMS	4.0 nm RMS	0.5 nm RMS

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

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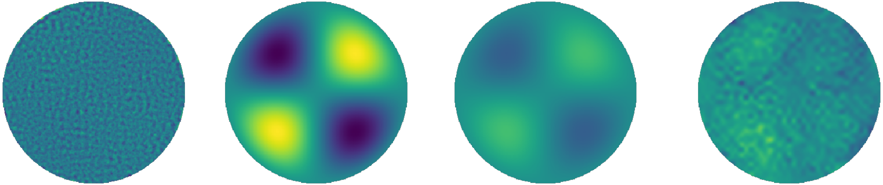

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129 nm RMS	10.0 nm RMS	4.0 nm RMS	0.5 nm RMS

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

Increase the controller gain by 2.5 ?

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

Using the KL basis of the DM KL_1 ... KL_N

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

$\mathbf{Rec}$: flat-phase modal command matrix

Update $\mathbf{Rec}$ with:

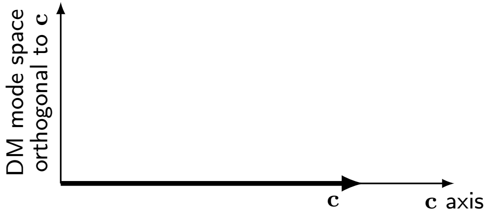
$$\mathbf{Rec}[\mathrm{OGMC}] = \begin{bmatrix} G_{\mathrm{opt}}(\mathrm{KL}_1) & & 0 \\ & \ddots & \\ 0 & & G_{\mathrm{opt}}(\mathrm{KL}_N) \end{bmatrix} \cdot \mathbf{Rec}$$

$\rightarrow$ Each mode of basis compensated appropriately

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

Reconstruction with optical gain - DM space analysis

Let $\mathbf{c}$ be a DM mode



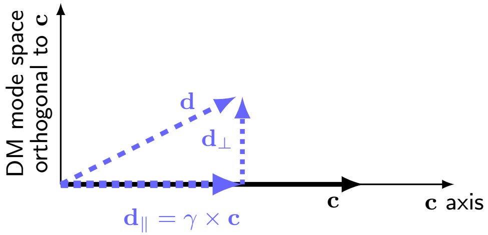
Reconstruction with optical gain - DM space analysis

Let $\mathbf{c}$ 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 $\mathbf{d}_{\perp}$



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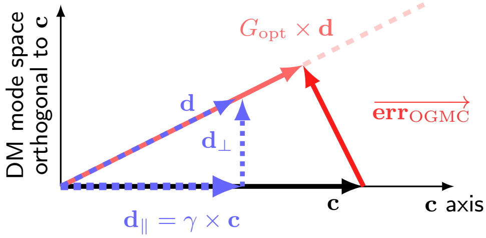
Good rescaling for ϕ around ϕ_{ref}:

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



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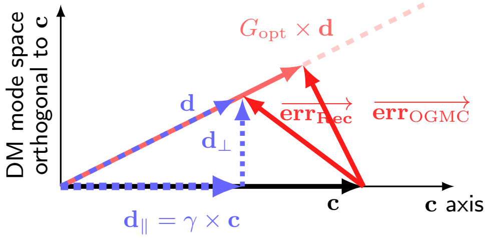


Quantities to analyse:

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

Analyzing Optical Gain:
How much to apply, for what performance ?

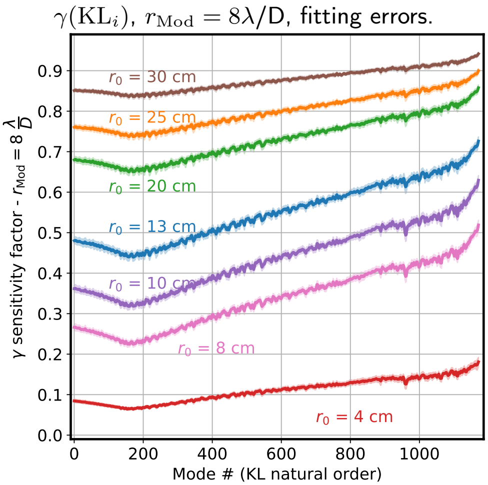
Simulation parameters

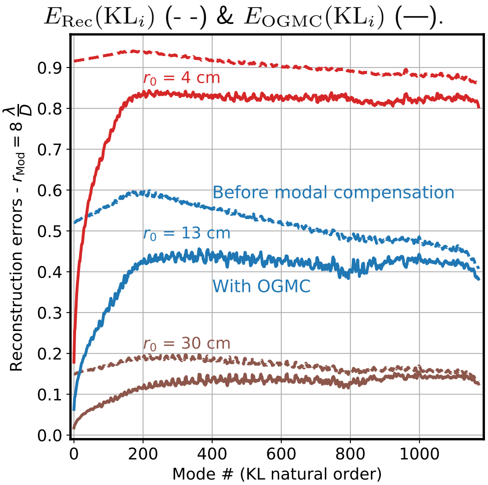
Numerical simulations configuration

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. Measurements λ_{PWFS} PWFS modulation	61×61 all illuminated pixels 658 nm Circular; selectable r_{Mod}.
Noise	$0.3\ e^-$
Controller	Modal integrator 2 frames latency
λ_{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

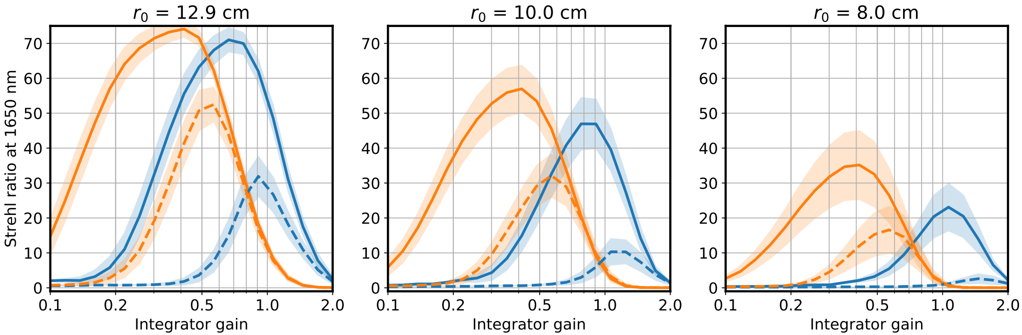
Eliminate loop gain contribution
What does OGMC bring on top of it ?

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



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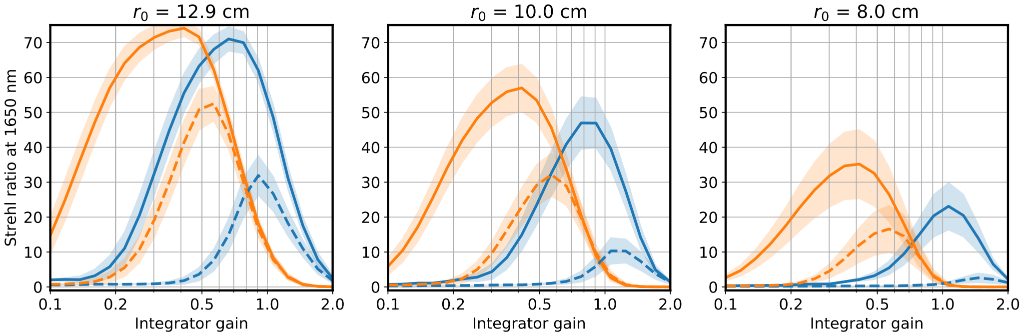
Without noise:

- 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



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$\mathrm{Mag}_R = 16.0$ (.44 ph/px/fr @ 500Hz):

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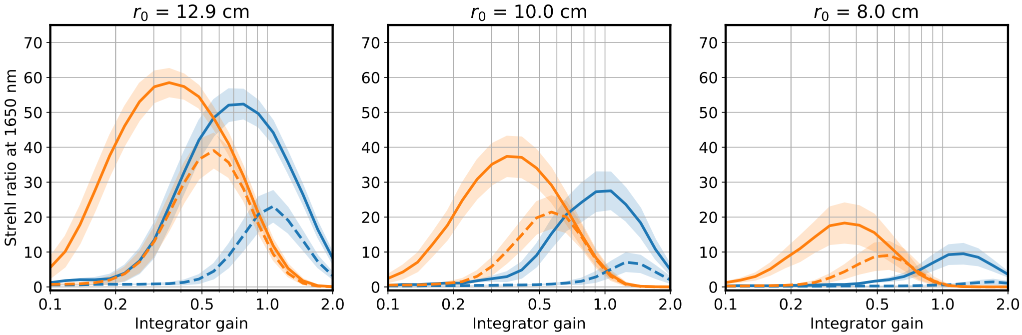

End-to-end OGMC comparative performance – for static and known r_0

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What does OGMC bring on top of it ?

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

$\mathrm{Mag}_R = 17.0$ (.18 ph/px/fr @ 500Hz):

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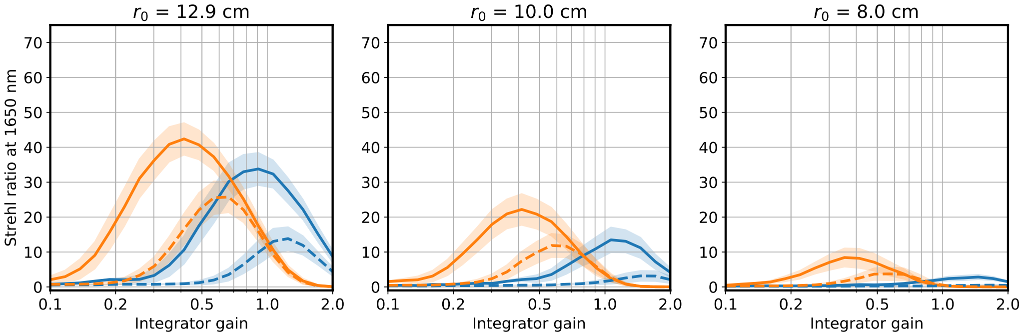
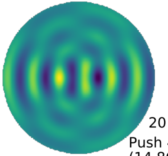


A method for sky operations:
Poking some modes for automatic compensation updates

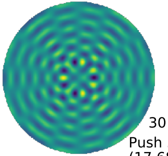
Mirror poking and PWFS frequency-locked detection – $r_{\mathrm{Mod}} = 8\lambda/D$, $\mathrm{Mag_R} = 16$, $r_0 = 13$ cm

KL #82



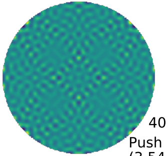
20 Hz
Push 42.0 nm P-P
(14.86 nm RMS)

KL #394

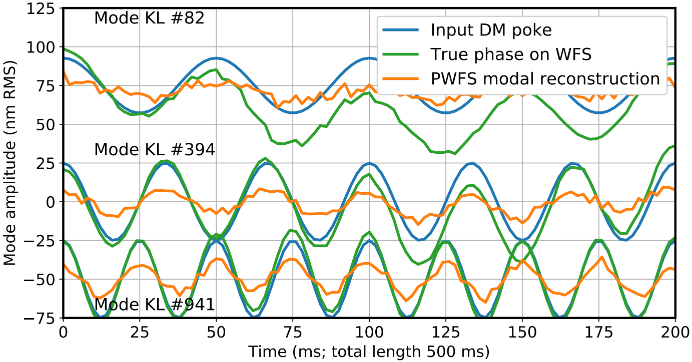


30 Hz
Push 50.0 nm P-P
(17.68 nm RMS)

KL #941



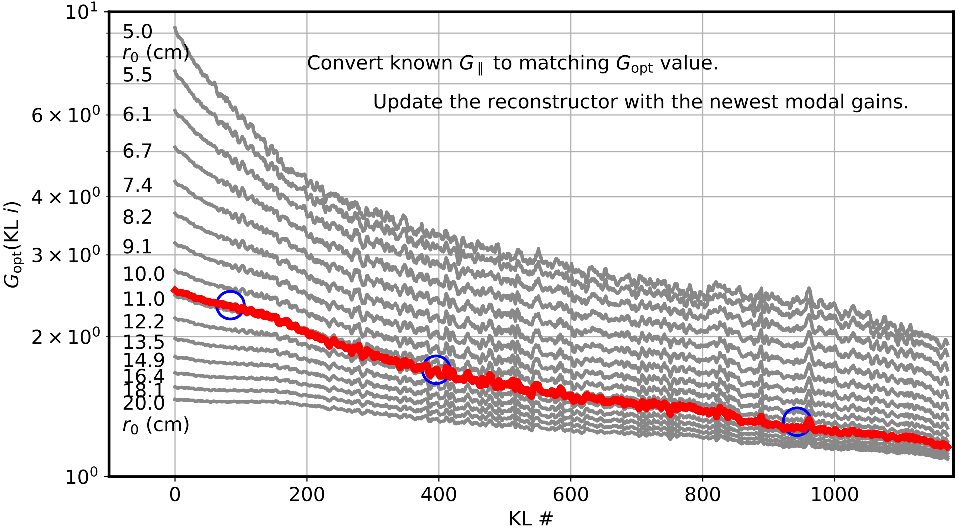
40 Hz
Push 10.0 nm P-P
(3.54 nm RMS)



- 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: $G_{\mathrm{opt}}(\#82) = 2.4$, $G_{\mathrm{opt}}(\#394) = 1.7$, $G_{\mathrm{opt}}(\#941) = 1.3$

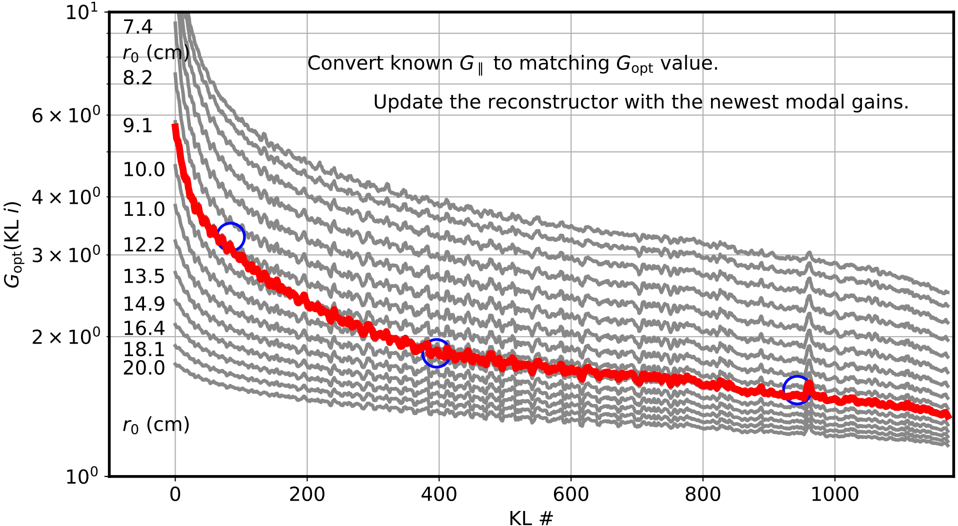
Abaqus interpolation - Measuring all modes

Still $r_{\mathrm{Mod}} = 8\frac{\lambda}{D}$, $\mathrm{Mag_R} = 16$, $r_0 = 12.9$ cm
Abaqus obtained from numerical simulations once. At most 1-2 d. calculations for ELT model.



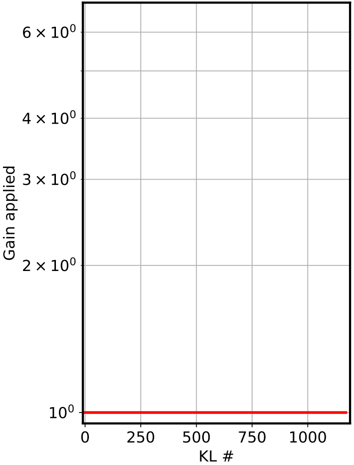
Abaqus interpolation - Measuring all modes

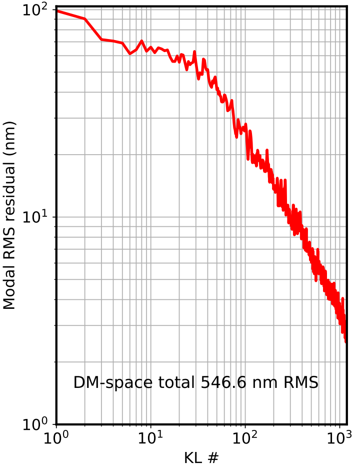
Another example: $r_{\mathrm{Mod}} = 2\frac{\lambda}{D}$, $\mathrm{Mag_R} = 16$, $r_0 = 12.9$ cm



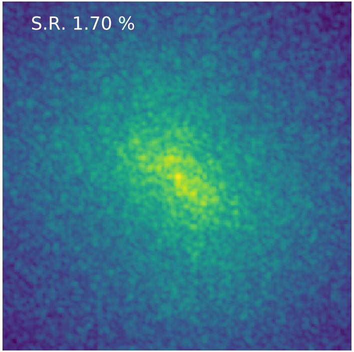
Bootstrapping without knowledge of atmospheric conditions

$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



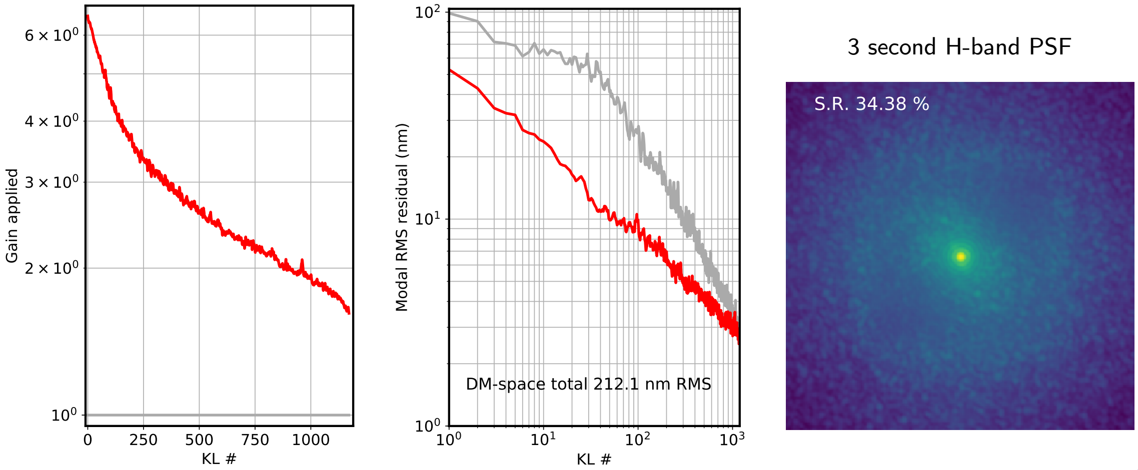


3 second H-band PSF



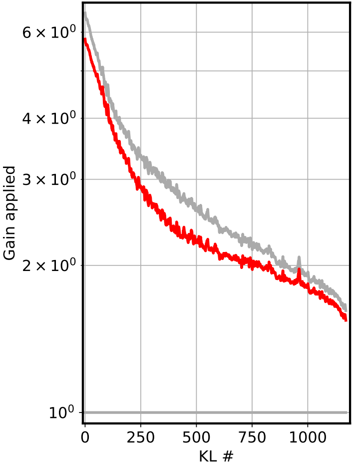
Bootstrapping without knowledge of atmospheric conditions

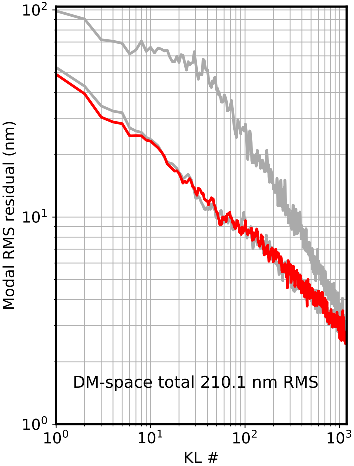
$r_0 = 10.0$ cm (constant, unknown to the AO), $r_{\mathrm{Mod}} = 6\frac{\lambda}{D}$, $\mathrm{Mag}_{\mathrm{R}} = 16$.
Step 1: After 1 pass of mode poking for .5 sec



Bootstrapping without knowledge of atmospheric conditions

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





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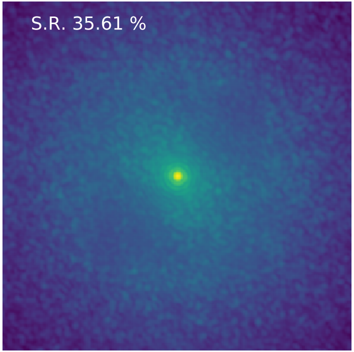
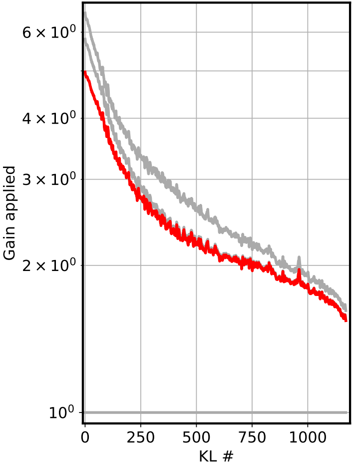
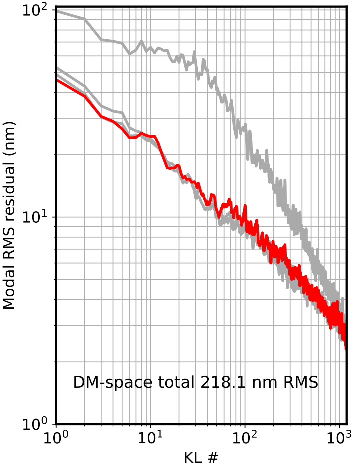


Bootstrapping without knowledge of atmospheric conditions

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





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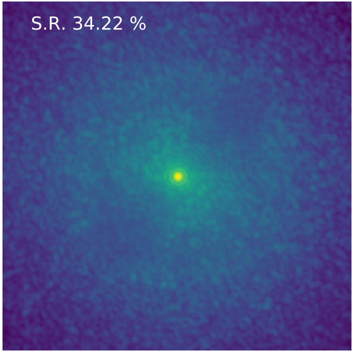
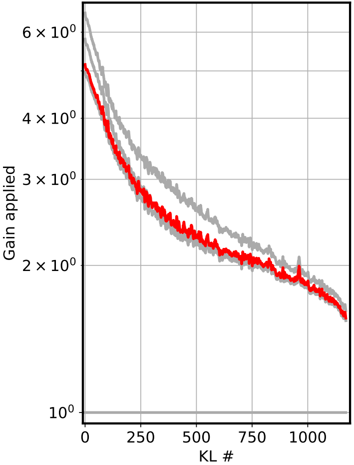
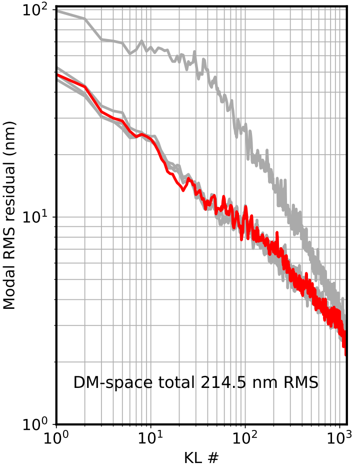


Bootstrapping without knowledge of atmospheric conditions

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





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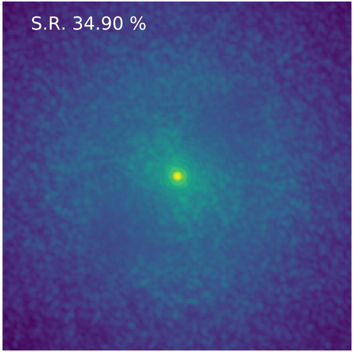
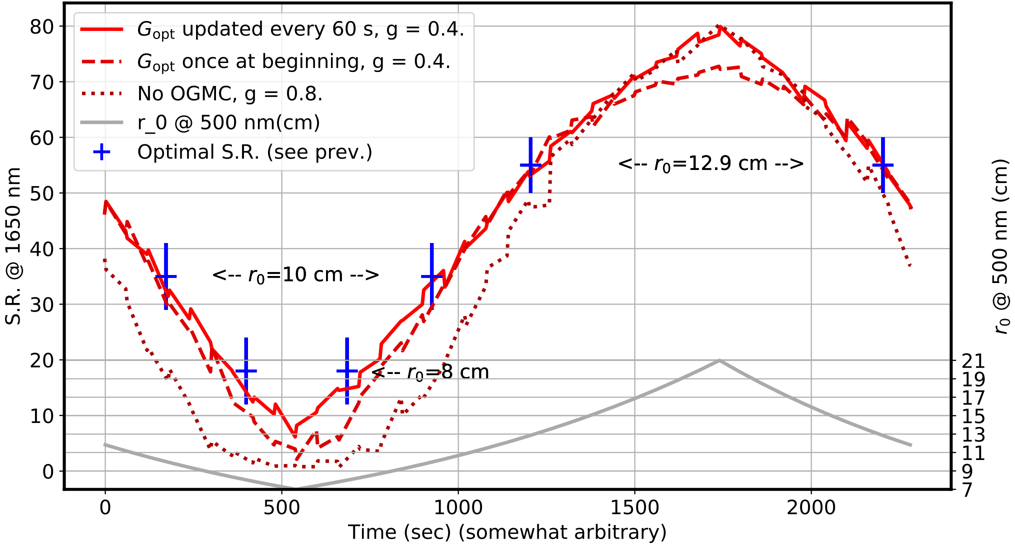


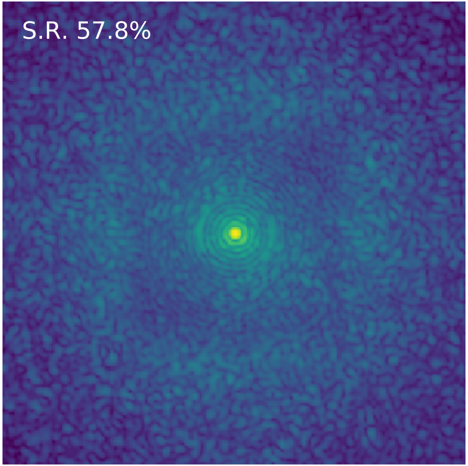
When r_0 varies wildly/widely: poke & update every minute for 6% r_0 variation steps



Performance during the poking cycle

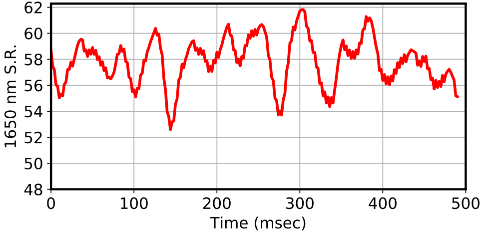
Bright star - r_0= 10 cm

LE PSF across 500 msec. poke cycle

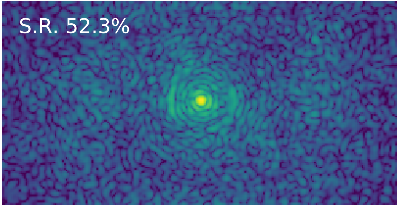


Nominal LE SR: 55$\pm$3%

Continuous imaging quality during pokes



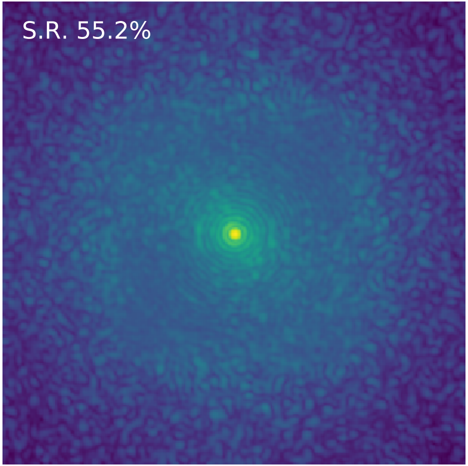
Worst 10 msec PSF



Performance during the poking cycle

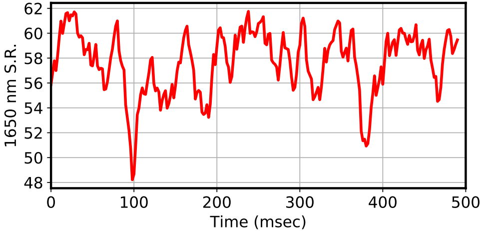
$\mathrm{Mag_R}$ = 16 - r_0= 12.9 cm

LE PSF across 500 msec. poke cycle

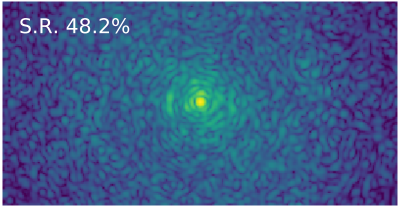


Nominal LE SR: 54±4%

Continuous imaging quality during pokes



Worst 10 msec PSF



Proposed operational procedures

The Strehl is not reduced for exposures over the whole poke cycle.

- Artifacts will be optimized by a better choice of modes
- Known disturbed PSFs can be provided to astronomers

But Strehl may drop by 5-10% for short snaps within the poke cycle.

Perspectives for operations:

- Software interaction between the AO and the spectro-imager
- If imaging sequences of short exposures:
  $\rightarrow$ Imager told to hold during poke sequences (0.5 sec every min.)
- If doing long exposures:
  $\rightarrow$ AO pokes and recalibrates gains during the exposure, artifacts are diluted.

Summary

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:

- Perf. comparable to when r_0 is known/static
- Stable across very long durations
- Self adaptive to large seeing changes
- Little interference with science

Future work:

- Improve, understand, optimize duration, amplitudes, SNR, misc. parameters...
- Porting this pipeline on demonstrator bench
- On-sky demonstration; WHT 2020-2021 ?
- Integration in MICADO SCAO RTC

On our way for a continuously better PWFS cookbook !