MODULATION STRATEGIES TO MITIGATE ISLAND EFFECT WITH THE PYRAMID WAVEFRONT SENSOR

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OVERVIEW

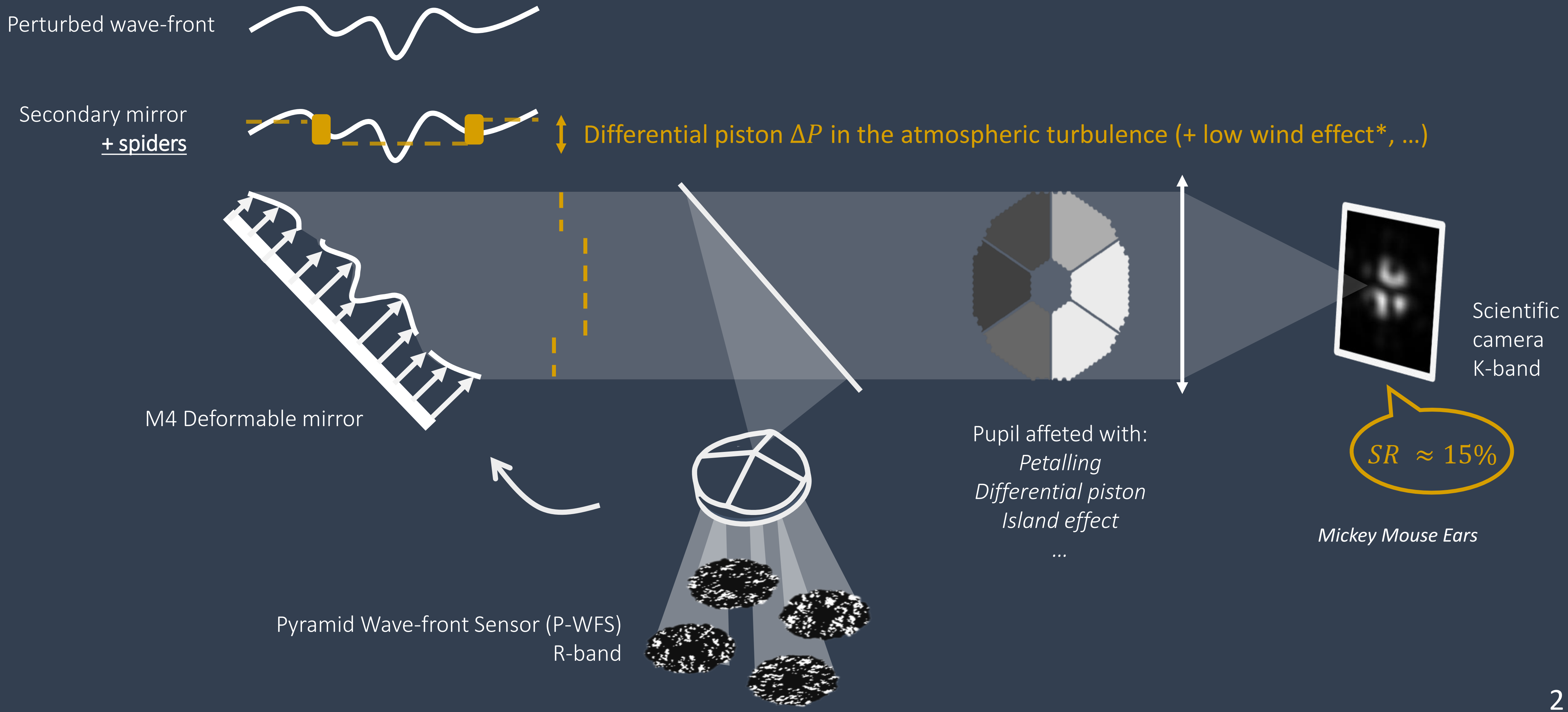
1. THE PROBLEM OF ISLAND EFFECT : CAUSES AND CONSEQUENCE

2. THE PYRAMID RESPONSE TO ISLAND EFFECT

3. MITIGATION STRATEGIES

I. THE PROBLEM OF SEGMENTED PUPIL

1. Island effect description



Low wind effect on VLT/SPHERE: impact, mitigation strategy, and results, Milli et al, SPIE 2018

2. Simulation parameters for COMPASS, an end-to-end AO simulation tool

Target

K-band $\lambda_{science} = 2{,}2\mu m$

Turbulence

$r_0 = 12{,}9\ cm$ - $seeing = 0.8"\ @500\ nm$
$L_0 = 25\ m$
$\|v\| = 10\ m.s^{-1}$

Telescope

ELT-like pupil $\emptyset = 39\ m$
with six-legged spider of 51 cm thickness

Deformable mirror

M4-like with 4310 actuators
controlled using the Karhunen-Loeve modes of the mirror
Tip/Tilt
Correction @ 500 Hz

Wave-front sensor

Visible wavelength $\lambda_{P-WFS} = 700\ nm$
Modulation $r_{mod} = 3\frac{\lambda}{D}$
92 x 92 sub-apertures per pupil
No modal gain compensation

GOAL : Differential piston sensing with a pyramid on an ELT in the visible

Real-time end-to-end AO simulations at ELT scale on multiple GPUs with the COMPASS platform, **Ferreira, F. et al,** Proc. SPIE 10703 (2018)

I. THE PROBLEM OF SEGMENTED PUPIL

3. Differential piston ΔP drifting due to segmented pupil

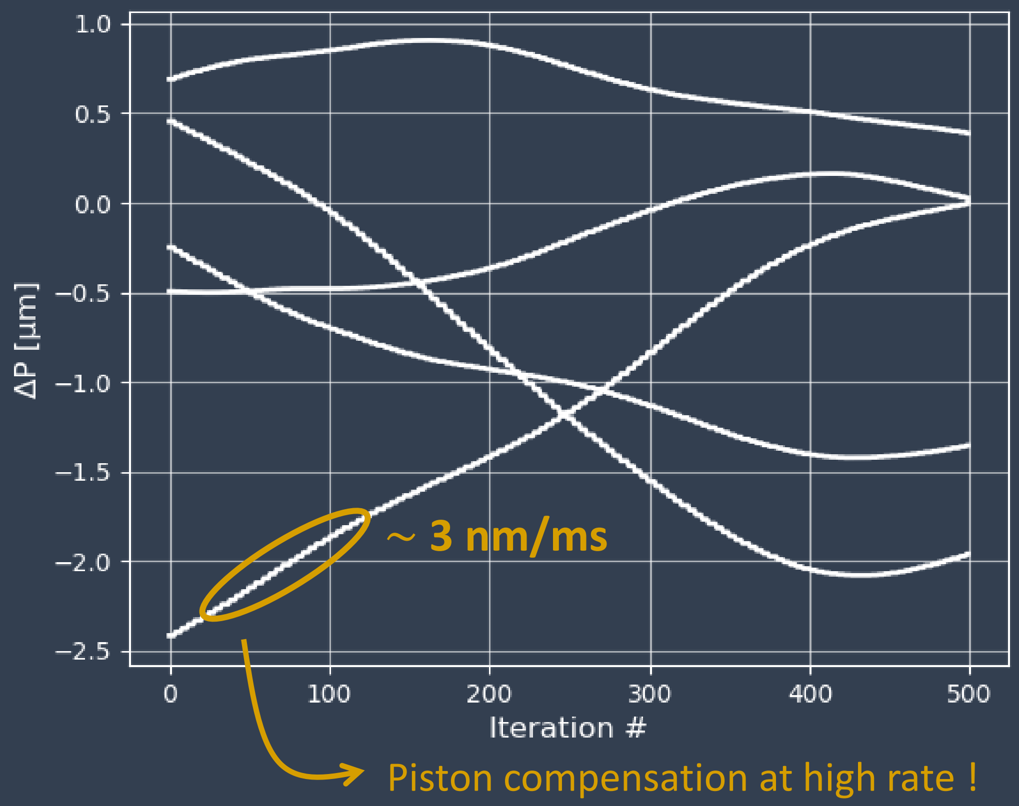
OPEN LOOP

atmospheric ΔP to be compensated

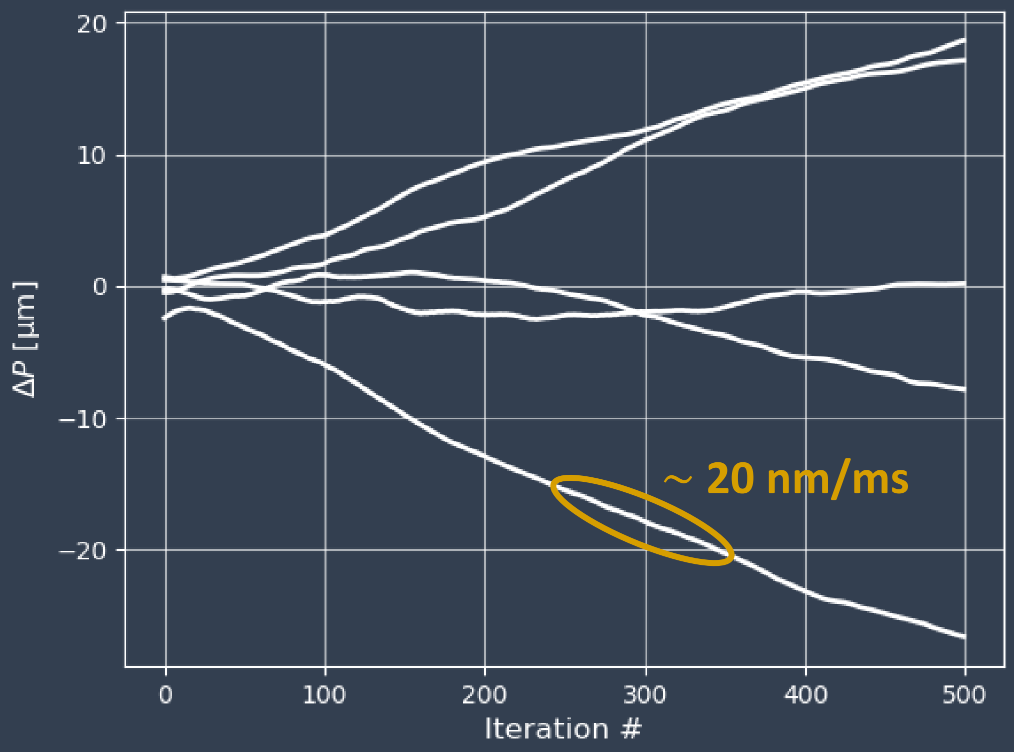
CLOSED LOOP

pyramid response implies a drifting of ΔP ...

Long exposure Strehl Ratio (K) ~ 15% with ΔP
against ~ 82% if compensated



mind
the scale !

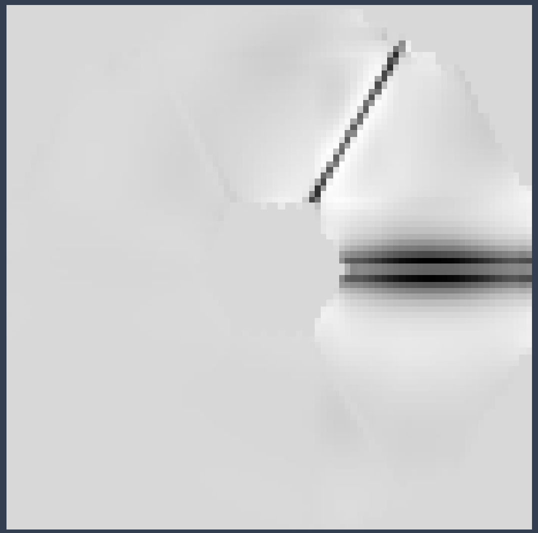


Sensing and control of segmented mirrors with a pyramid wavefront sensor in the presence of spiders, **Schwartz, N.,** arXiv (2018).

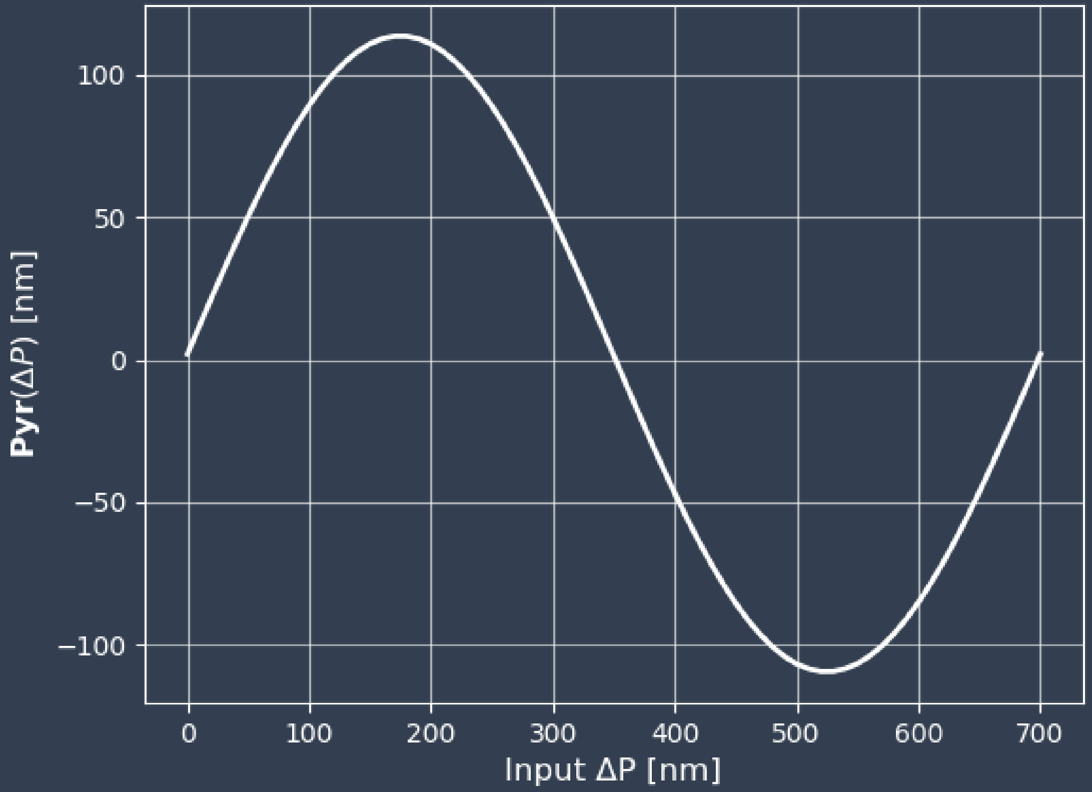
II. PYRAMID RESPONSE TO DIFFERENTIAL PISTON

1. DIFFRACTION LIMITED CONDITIONS

S_x map



Interferences of the diffracted beam split at the tip and edges of the pyramid
The effect is visible along the spiders

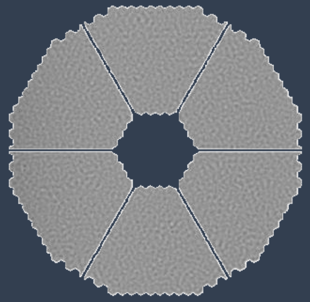


The pyramid has a sinusoidal response
Unlike other aberrations, the response doesn't saturate so the petal will settle around multiples of λ

Segmented telescopes co-phasing using a pyramid sensor, **Esposito, S. and Devaney, N.,** (2002).
Laboratory test of a pyramid wavefront sensor, **Esposito, S., Feeney, O., and Riccardi, A.,** Proc. SPIE (2000)

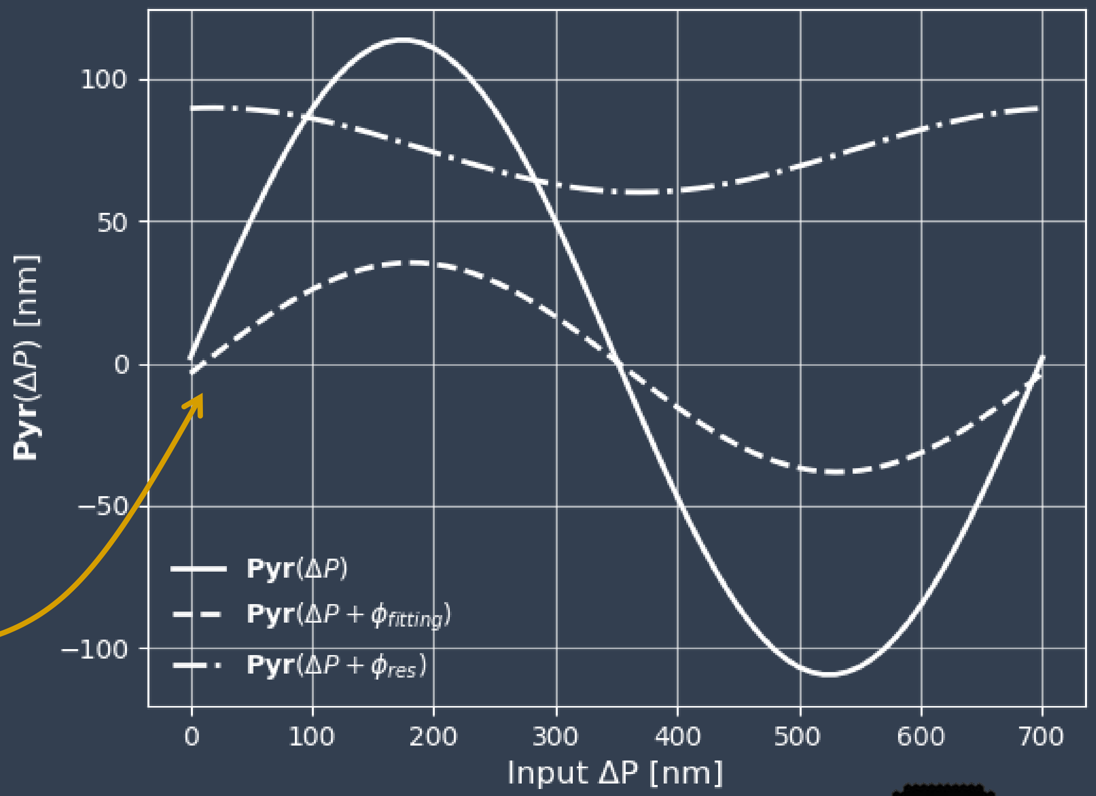
II. PYRAMID RESPONSE TO DIFFERENTIAL PISTON

2. UNDER PARTIALLY CORRECTED WAVEFRONT



$\phi_{fitting}$

Fitting phase depicting the best compensated wavefront error (high orders)



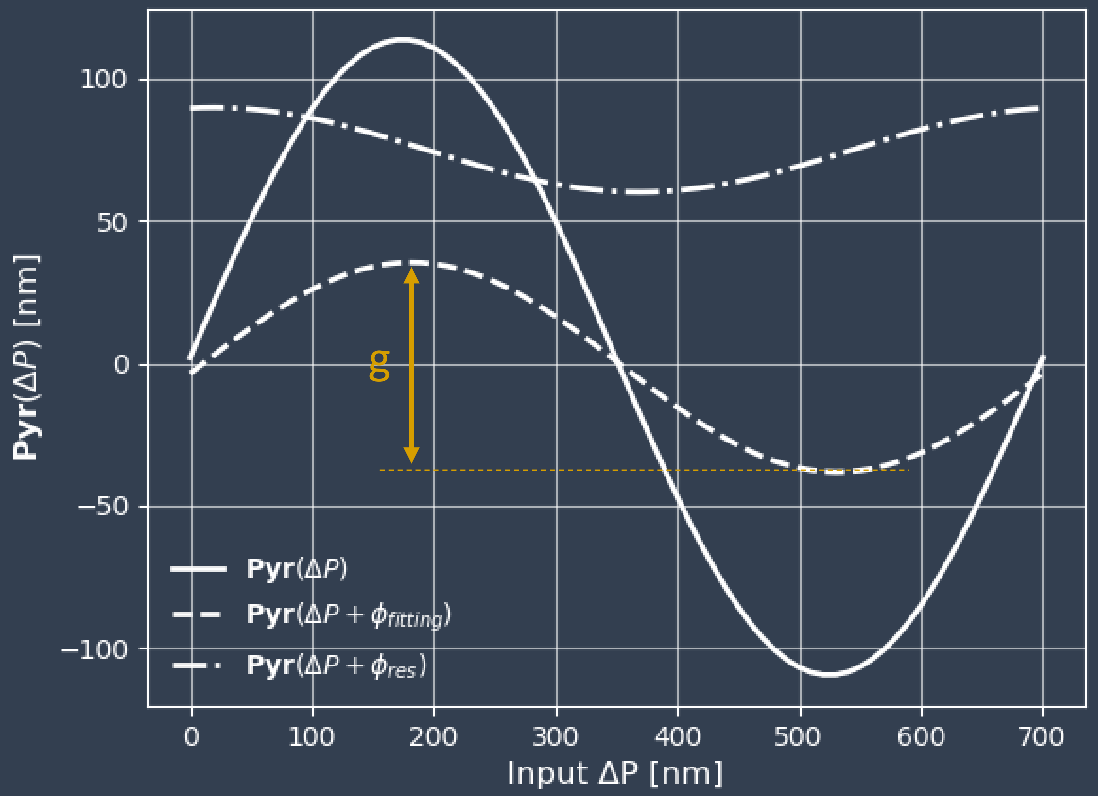
II. PYRAMID RESPONSE TO DIFFERENTIAL PISTON

2. UNDER PARTIALLY CORRECTED WAVEFRONT

Diffraction limited response differs from the response around residual phase errors:

- A flattened response

Optical gain compensation needs to be applied in order to recover the sensitivity



A telescope-ready approach for modal compensation of pyramid wavefront sensor optical gain, Deo et al, A&A 2019

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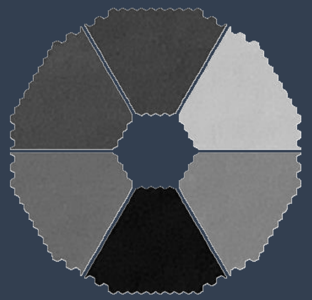
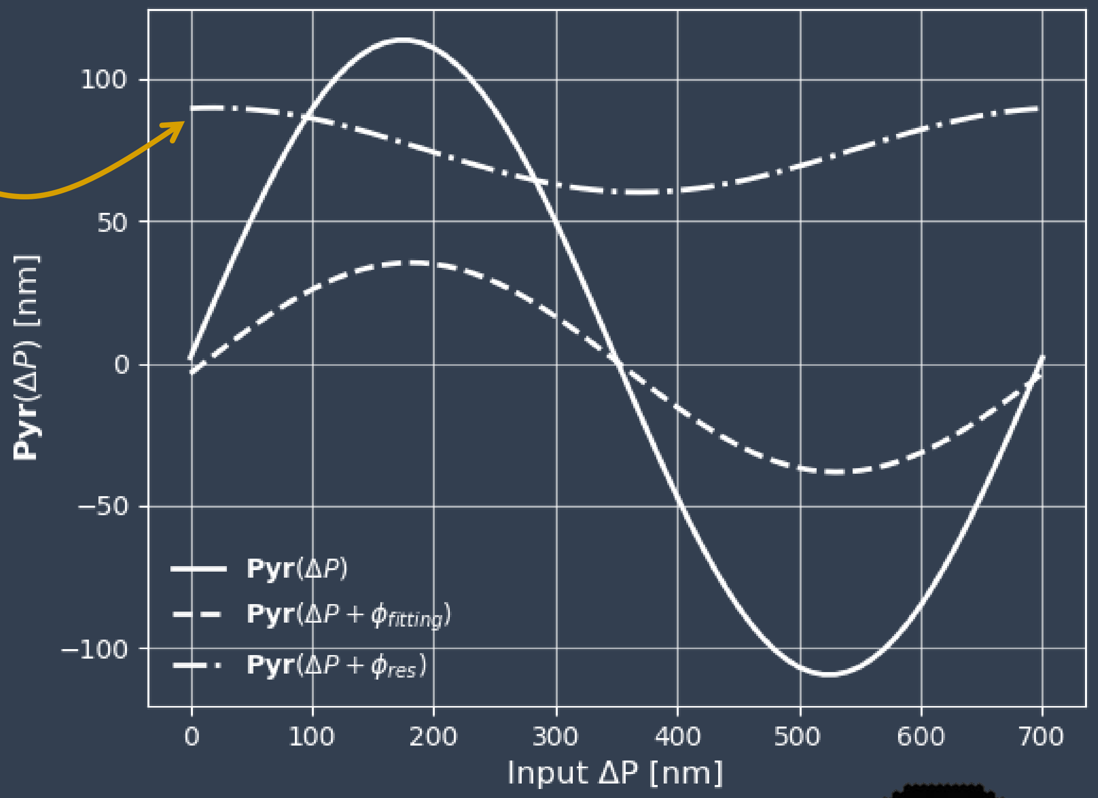


ϕ_{res}

Residual phase obtained from a closed loop AO system

$\phi_{res} - \Delta P$

post processed to remove the segment pistons contribution



II. PYRAMID RESPONSE TO DIFFERENTIAL PISTON

2. UNDER PARTIALLY CORRECTED WAVEFRONT

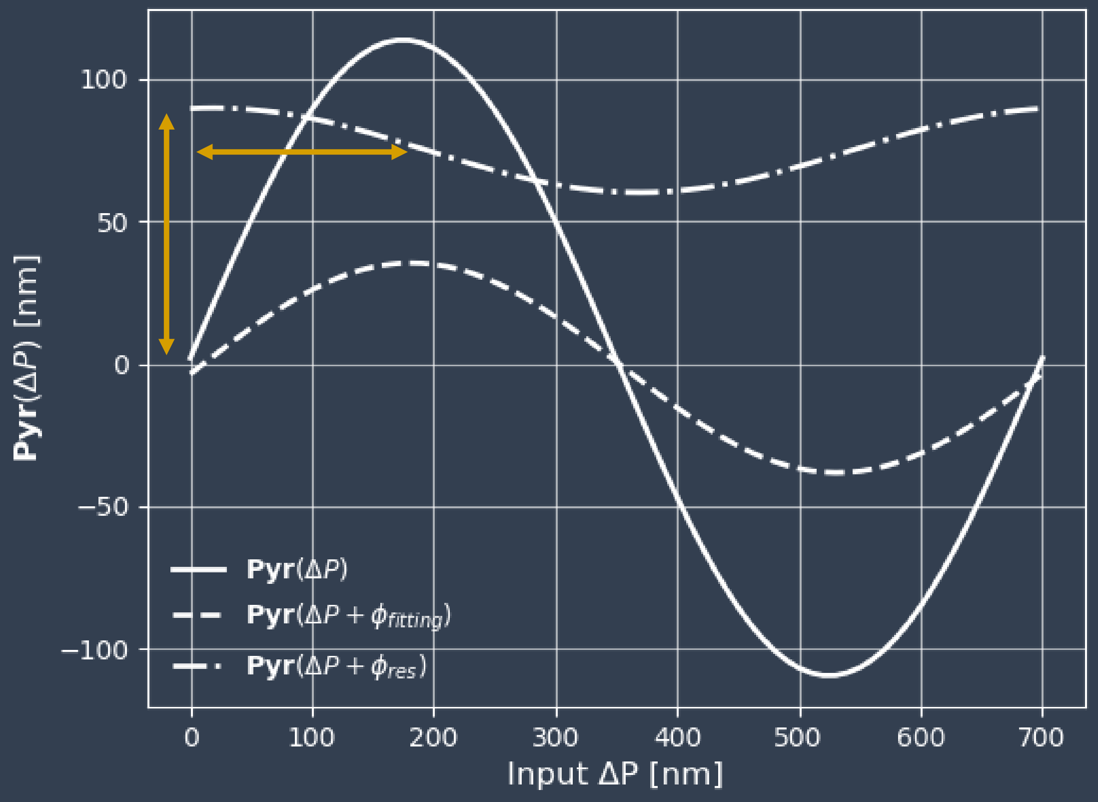
Diffraction limited response differs from the response around residual phase errors:

- **An offset and phase shift**

A non zero petal response when no differential piston is present: entanglement of the petal modes and other modes signal

Key issue leading to ΔP drift !

Is there a relation between ϕ_{res} and ΔP ?



CAN WE MAKE THE PYRAMID A PETAL SENSOR ?

III. MITIGATION STRATEGIES

0. By-passing the pyramid « spurious » behavior

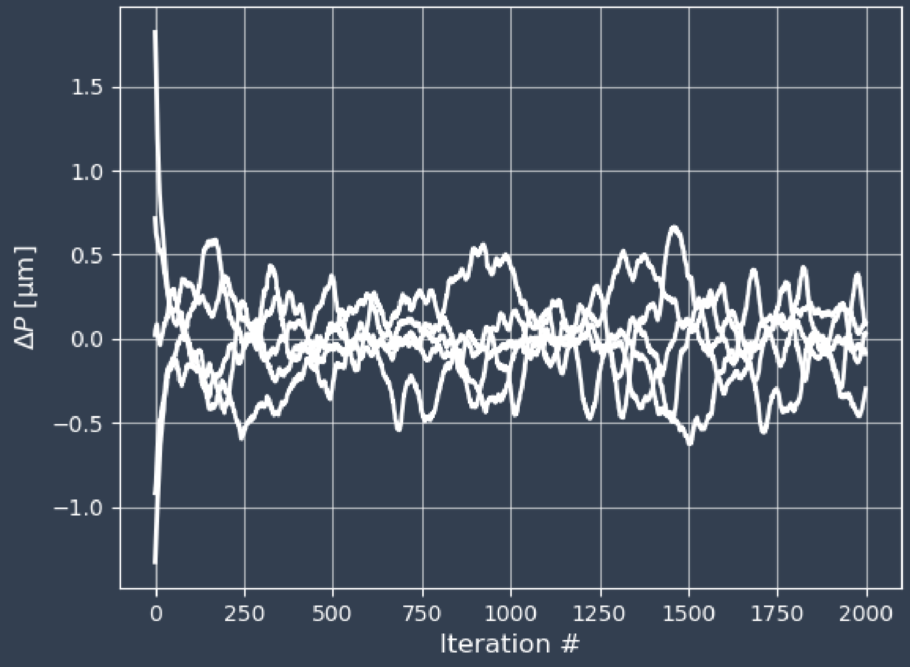
PERFECT ΔP CORRECTION

Long exposure SR = 82%

A MMSE is supposed to be the « best » reconstructor ...

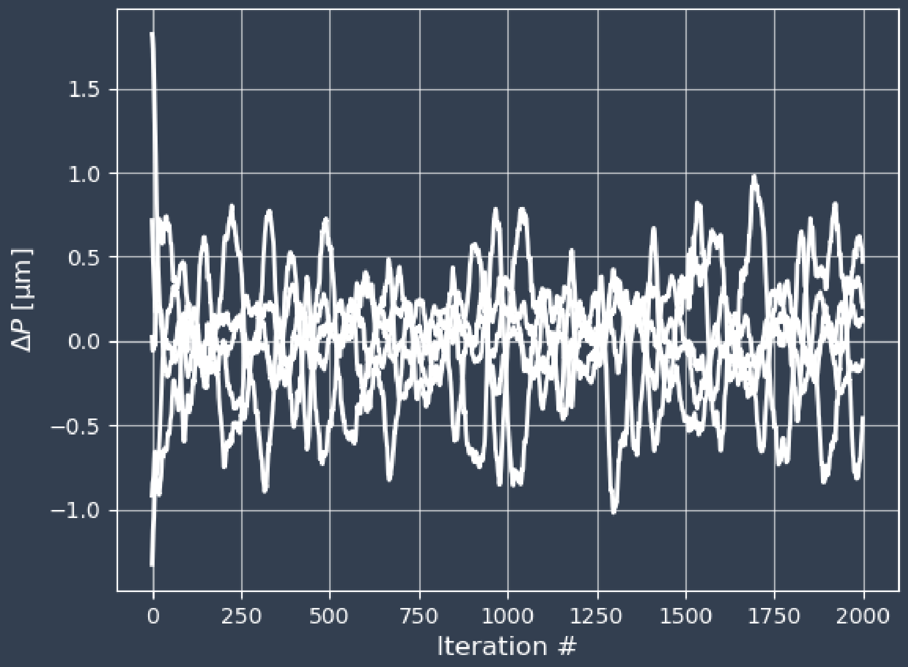
SLAVING METHOD

Long exposure SR = 68%



MMSE

Long exposure SR = 58%



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End-to-end simulations for the MICADO-MAORY SCAO mode, Vidal et al, AO4ELT5 (2017).

Analysis of the island effect for ELT MICADO MAORY SCAO mode, Bertrou-Cantou et al, AO4ELT6 (2019)

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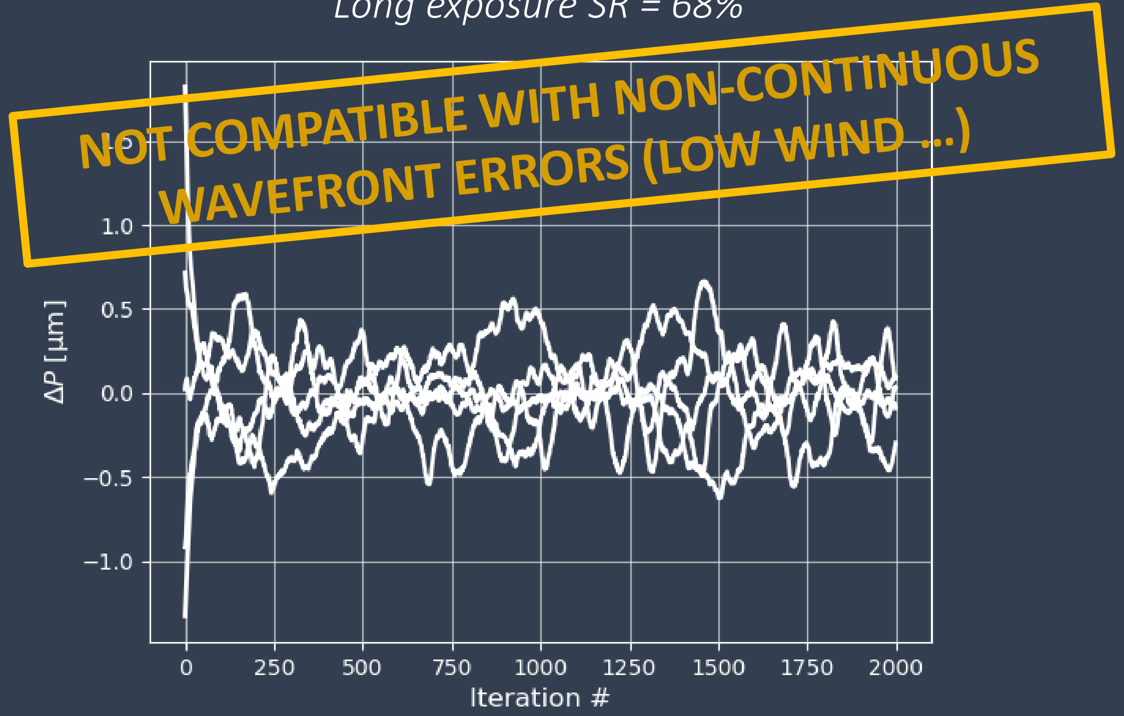

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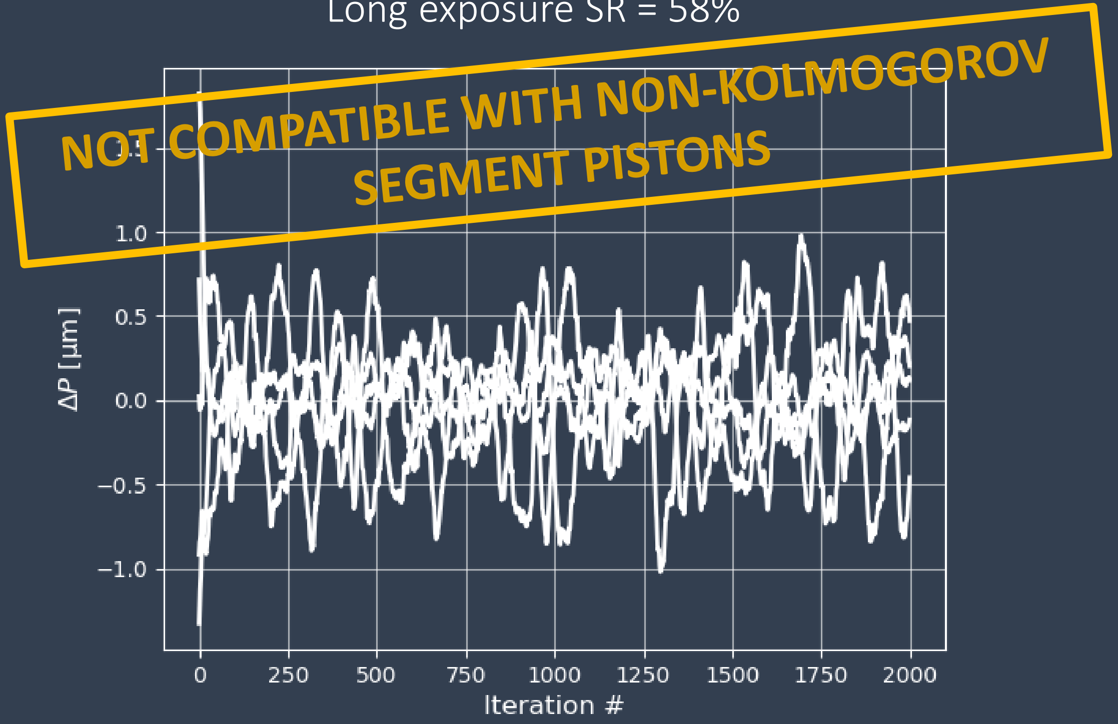

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III. MITIGATION STRATEGIES

1. Quantification of the differential piston error

hypothesis We set aside the λ ambiguity problem using an appropriate modulo operator so we get

$$-\frac{\lambda}{2} < \Delta P \leq \frac{\lambda}{2}$$

The reconstruction error is obtained computing
the standard deviation of the 5 differential pistons:

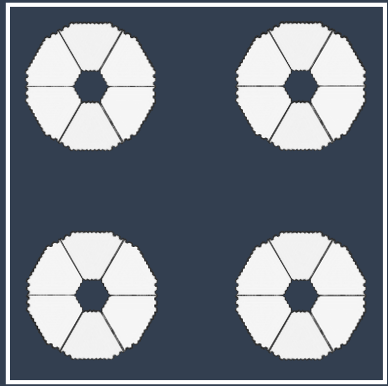
$$\sigma_{rec-\Delta P} = \sqrt{\frac{1}{5}\sum_{i=1}^{5}\langle(\Delta P_i - \overline{\Delta P})^2\rangle}$$

Statistical average is obtained using 2000 wavefront realizations (4 secs @500 Hz)

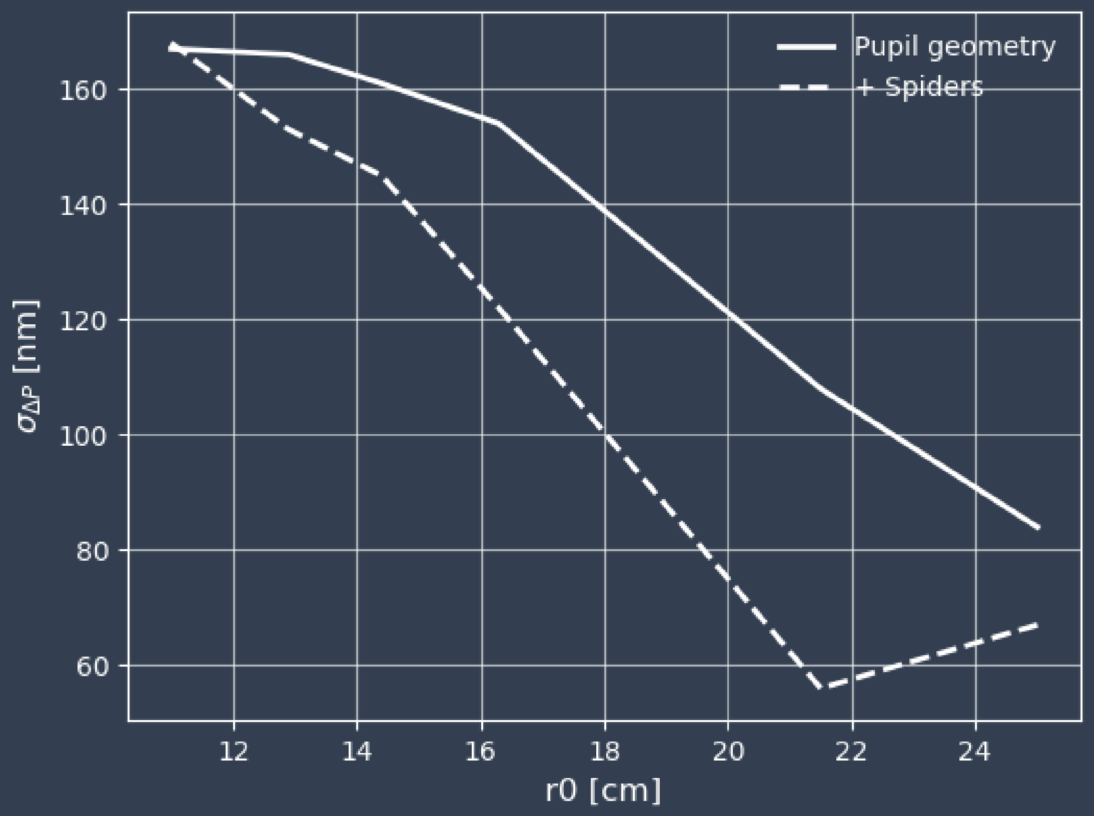
III. MITIGATION STRATEGIES

2. Valid pixels selection

Pupil geometry



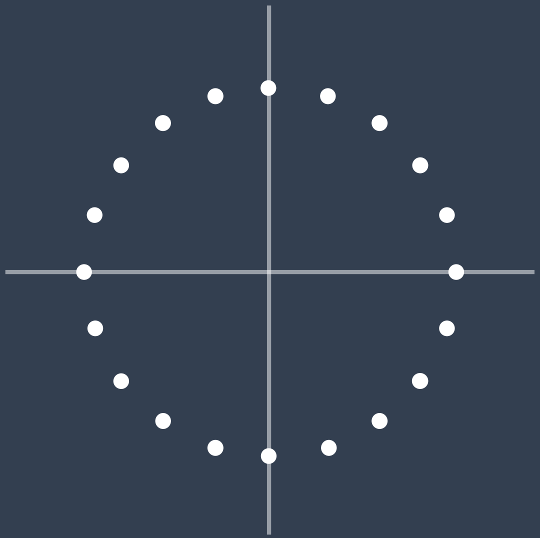
The pixels selection doesn't follow the pupil geometry to account for diffractive effects



III. MITIGATION STRATEGIES

3. A clover modulation

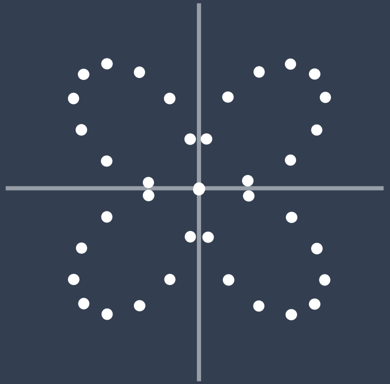
$$r_{mod} = 3\frac{\lambda}{D}$$



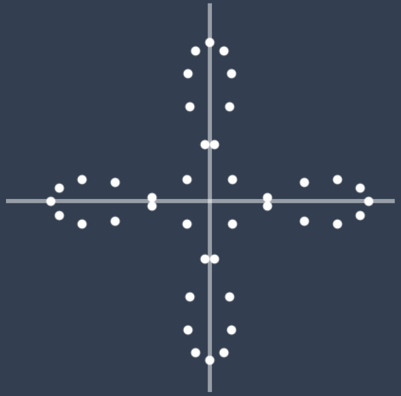
$$r_{mod} = 1\frac{\lambda}{D}$$

More time spent on edges and closer to the tip
But non linearity with other modes

clover



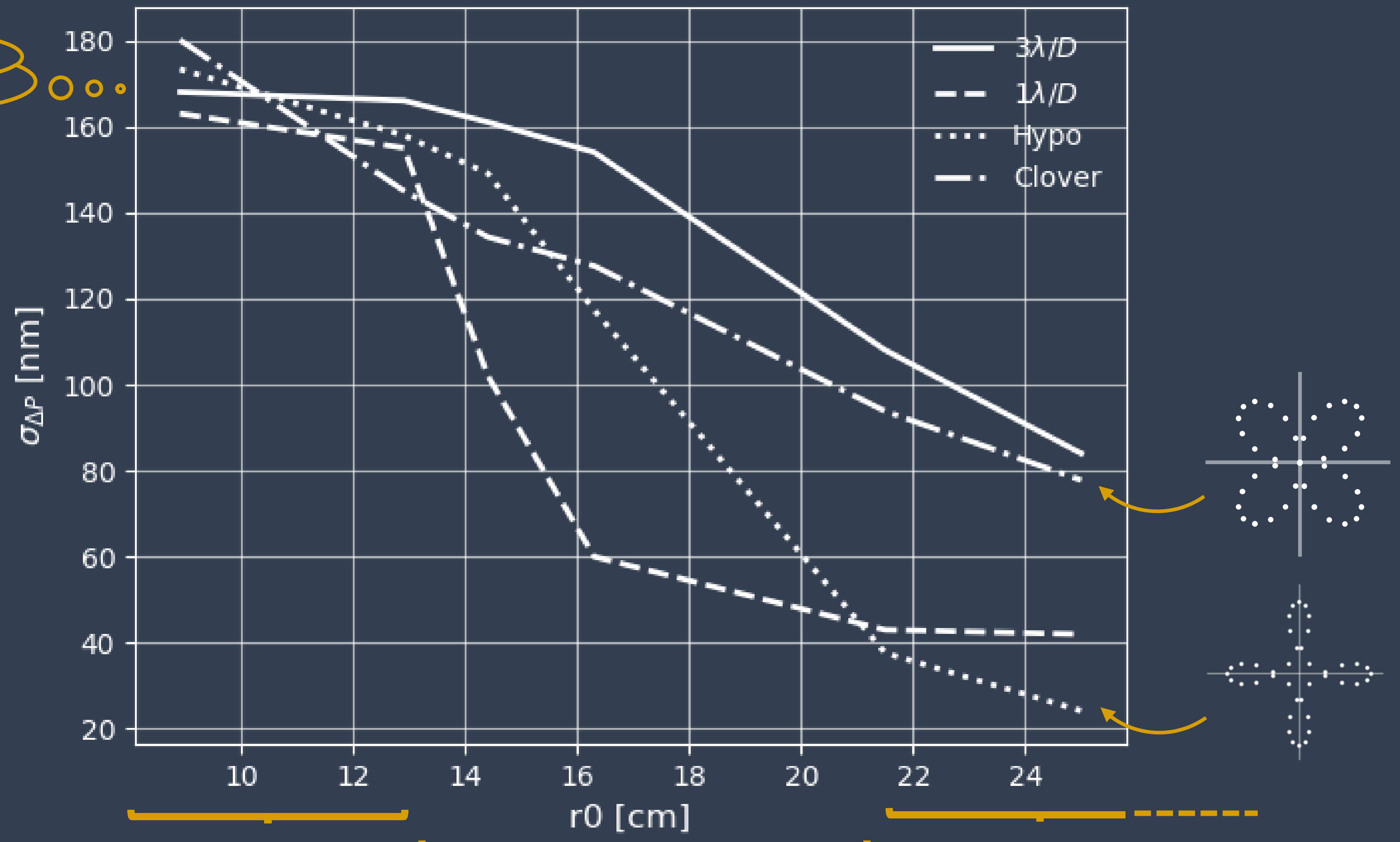
hypotrochoid



Compromise between petal sensing
and other modes sensing

III. MITIGATION STRATEGIES
3. A clover modulation

Close to the performance of randomly applied petal modes



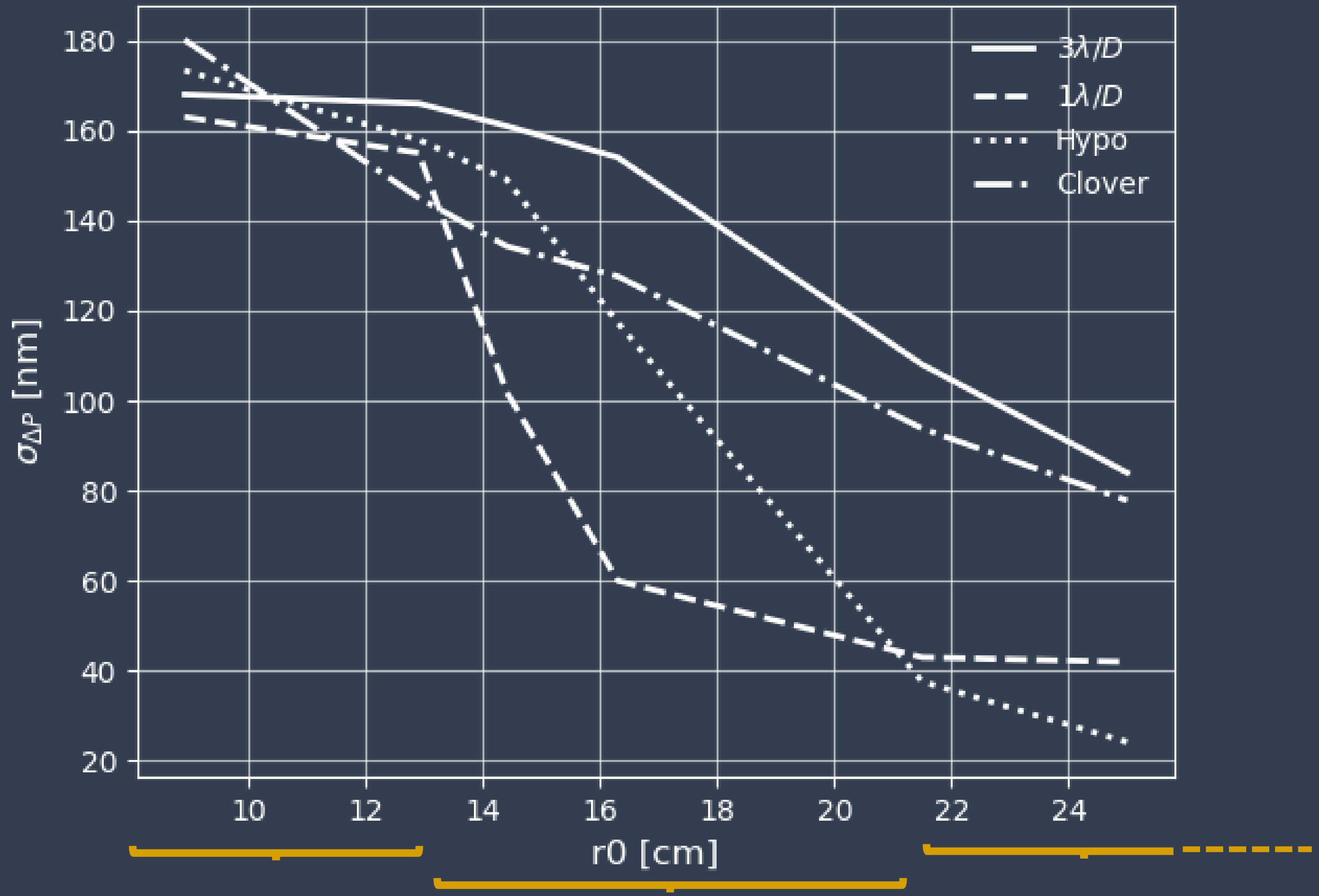
Miscorrection of ΔP

Decrease of the error

Correction regime

III. MITIGATION STRATEGIES

3. A clover modulation



Miscorrection of ΔP

Decrease of the error

Correction regime

Reduction of the circular modulation radius
→ better than attempting eccentric ones

Petal modes VS higher order modes correction
→ no win-win solution

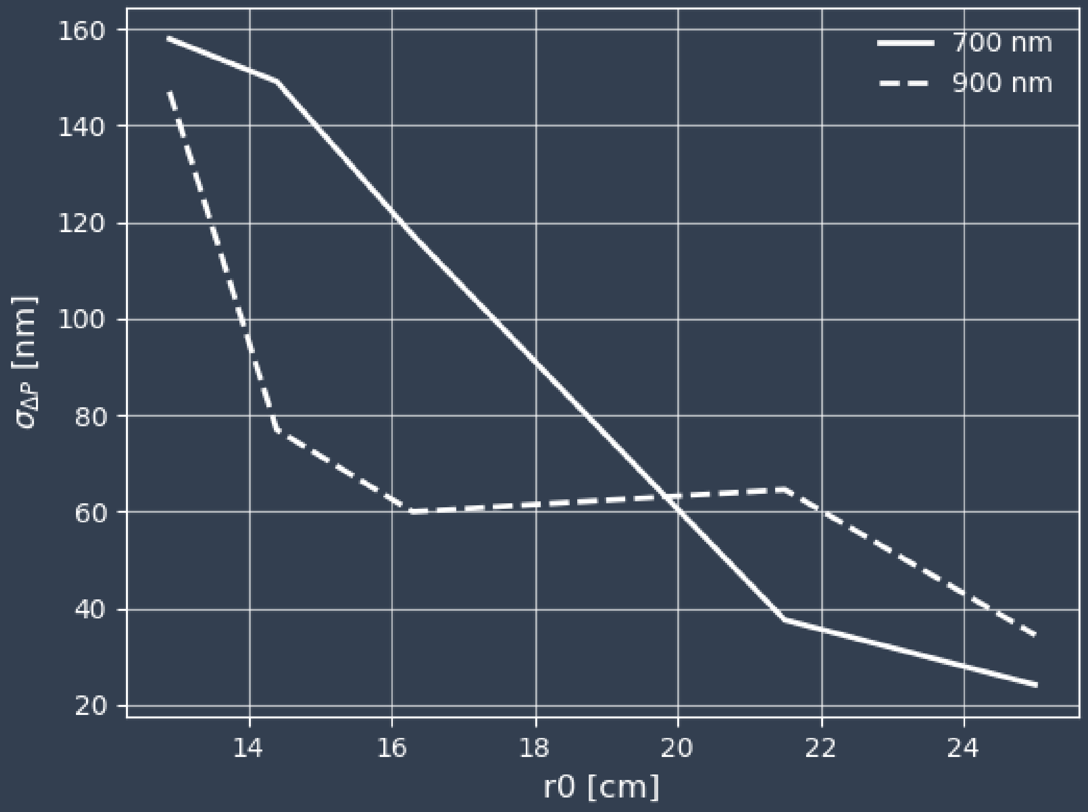
Whatever the modulation strategy
→ the plateau of uncorrected ΔP persists for median/bad seeing conditions

III. MITIGATION STRATEGIES

4. Wavelength choice impact

Whatever the strategy is, the plateau persists …

… only one solution helps : increase the wavelength



For a hypotrochoid modulation

CONCLUSION AND PERSPECTIVES

GOAL : Differential piston sensing with a pyramid on an ELT in the visible

under partially corrected wavefront ⤴ ⤴ **at a high rate $\approx 500\ Hz$**

WE TRIED :

- To understand the reason of the differential piston mismeasurement with the pyramid → Low order modes in the wavefront residuals drastically perturb the ΔP measurements. Dig deeper in the modal gain compensation, and probably cross-correlation of petal modes and other modes signal
- To optimize the modulation in order to get a good sensitivity for the petal modes AND the other modes → Results are not terrific: if an improvement exists, the plateau for bad atmospheric conditions persists
- To increase the wavelength → Only an increase of the wavelength actually helps but we are limited by the allocated wavelength range for the WFS ($\lambda < 900\ nm$)

↳ **A suitable « petalometer » seems to be a more reasonable solution**

Thank you for your attention