ELT differential piston sensing and pyramid WFS

WFS in the VLT/ELT Era V + AO Workshop Week II
15th October 2020

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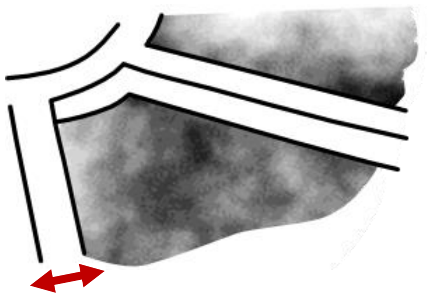
Université de Paris

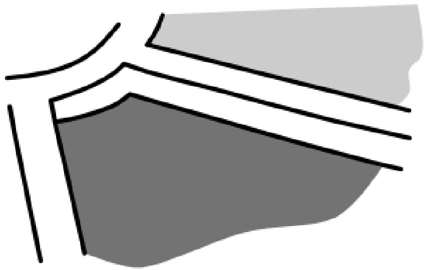
1. Differential piston causes

Atmospheric variations over spider gap



Break of the wave-front continuity

Mean per segment

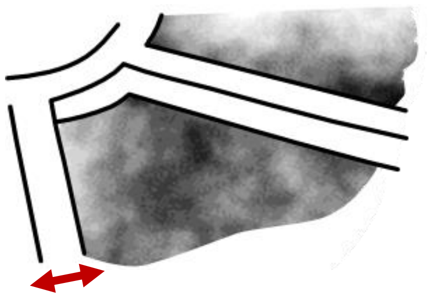


Amplitude $\Delta P \propto 1\ \mu m$

Timescale $\tau_{\Delta P} \propto ms$

1. Differential piston causes

Atmospheric variations over spider gap



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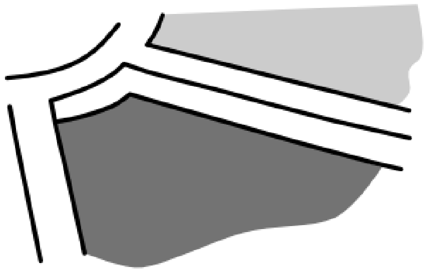
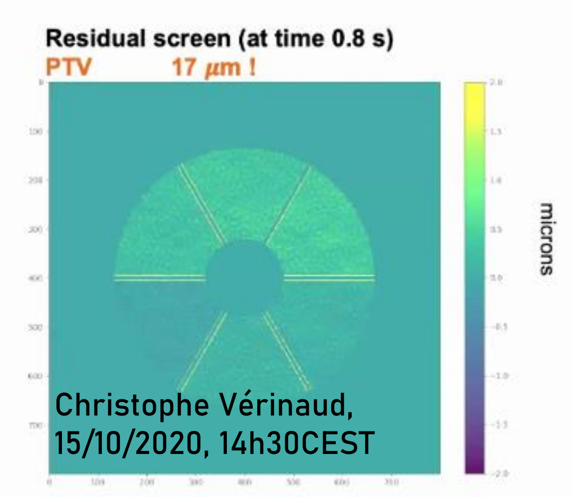
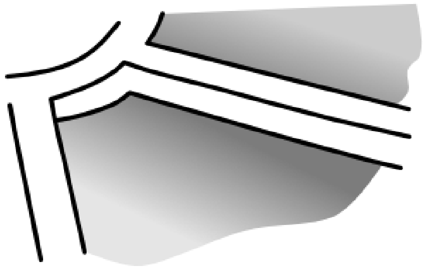


Amplitude	$\Delta P \propto 1\ \mu m$
Timescale	$\tau_{\Delta P} \propto ms$

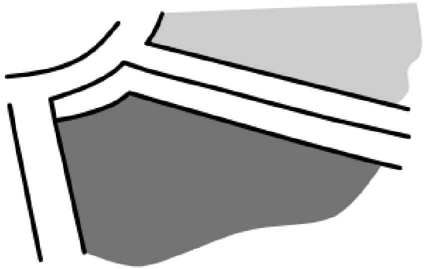


Low Wind Effect ?



Cooling of the spiders which creates local temperature gradients in the pupil

Mean per segment



1. Differential piston causes

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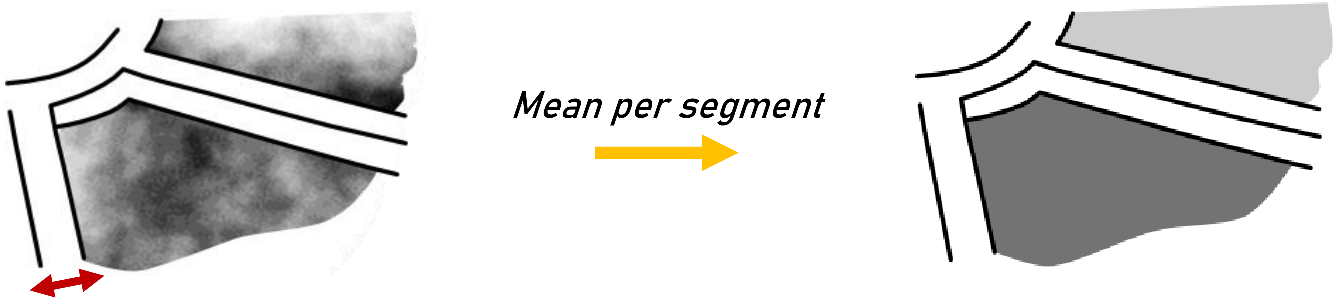

Amplitude	$\Delta P \propto 1\ \mu m$
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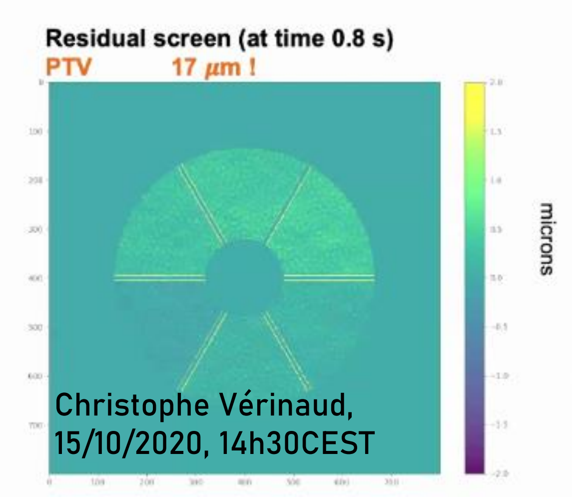
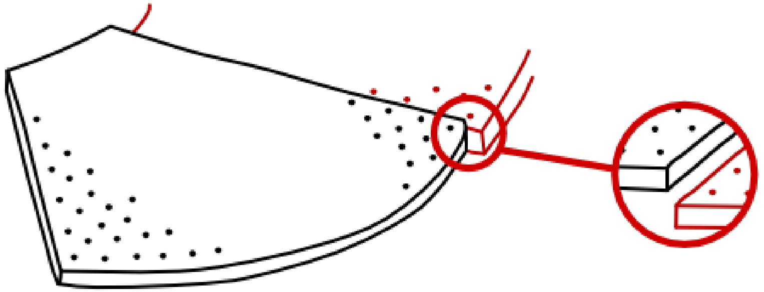


Low Wind Effect ?

Segmented deformable mirror



1. Differential piston causes

Atmospheric variations over spider gap

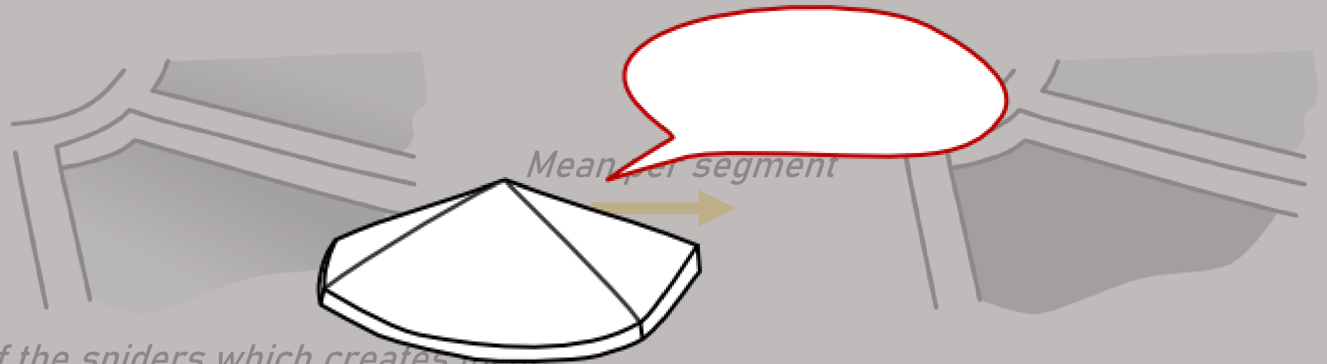
Amplitude $\Delta P \propto 1\ \mu m$

Timescale $\tau_{\Delta P} \propto ms$

Can the pyramid measure differential piston ΔP ?

Break of the wave-front continuity

Low Wind Effect ?

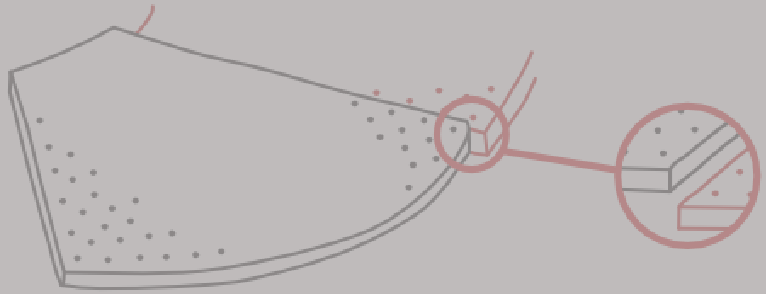


Amplitude $\Delta P \propto 100\ nm$

Timescale $\tau_{\Delta P} \propto$ second

Cooling of the spiders which creates local temperature gradients in the pupil

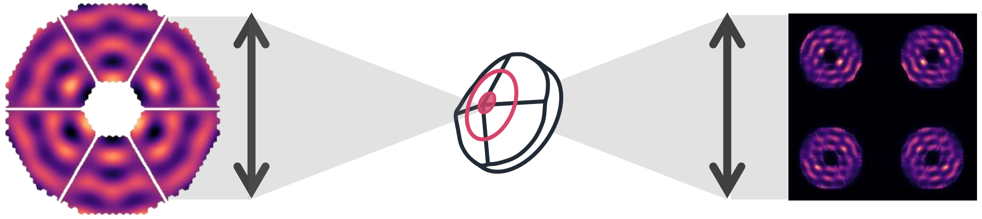
Segmented deformable mirror



2. Pyramid wave-front sensor

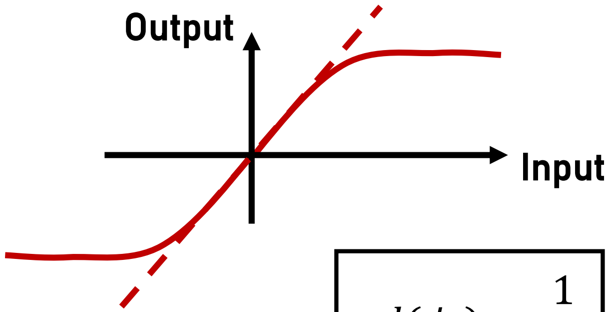
2.1. Performance criteria

Sensitivity



$$s(\phi_i) = \frac{\|Pyr\ Output(\phi_i)\|}{\|\phi_i\ Input\|}$$

Dynamic



$$y = ax + bx^3 + \dots$$

$$d(\phi_i) = \frac{1}{|b|}$$

Vérinaud 2004
Burvall 2006
Fauvarque 2016

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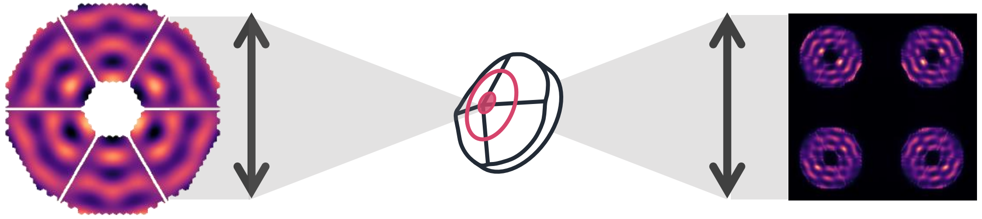

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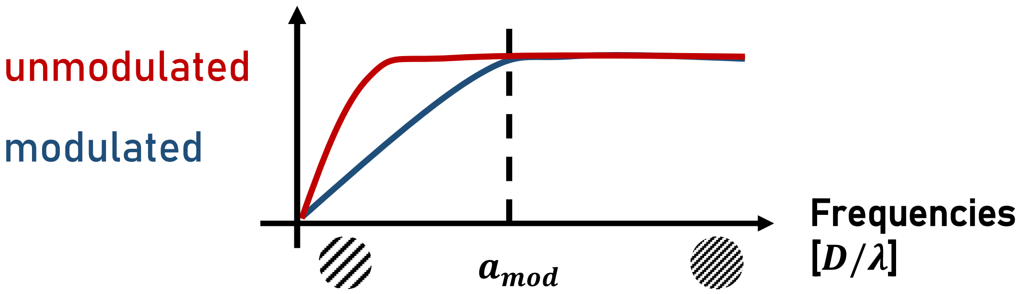

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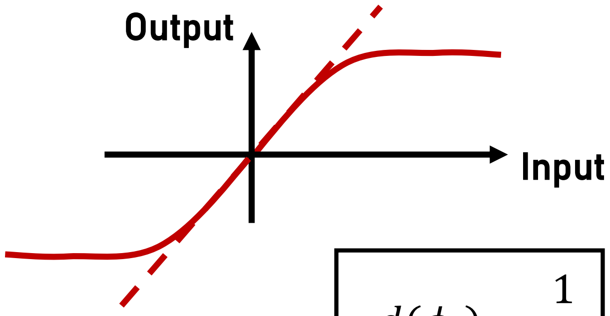

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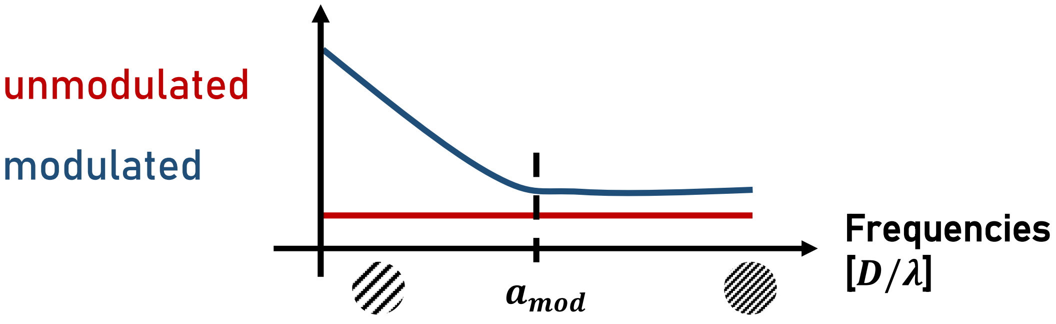


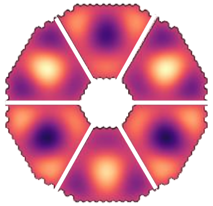
Trade-off between sensitivity and linearity

Vérinaud 2004
Burvall 2006
Fauvarque 2016

2. Pyramid wave-front sensor

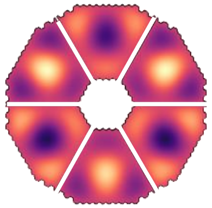
2.2. From calibration to operation

Calibration, SR=1



$10\ nm\ RMS\phi_i$

Pyramid Reconstruction



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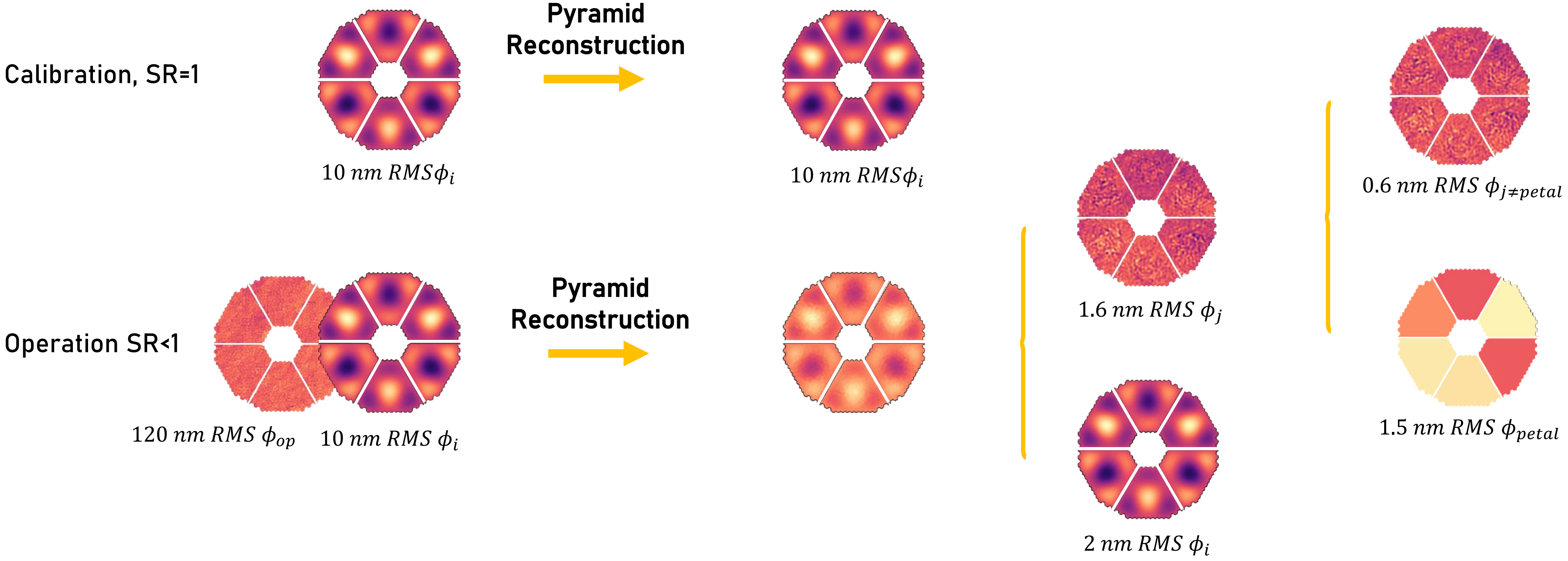

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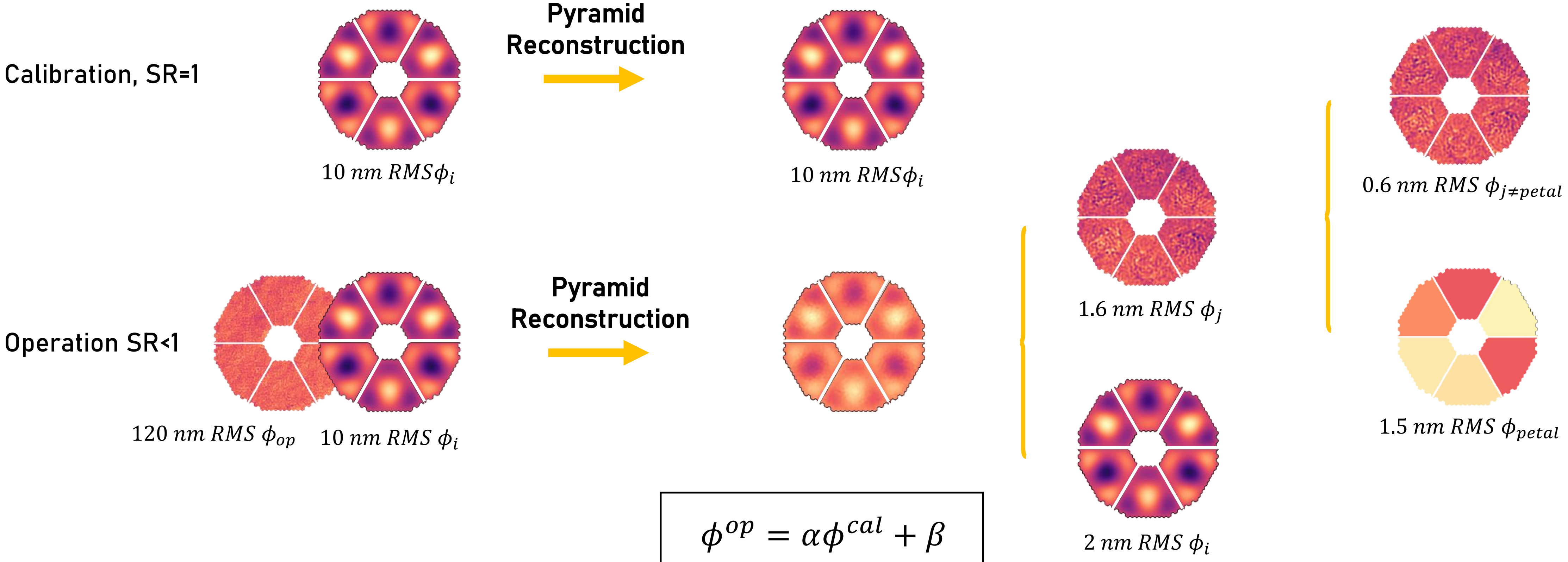


$$\phi^{op} = \alpha \phi^{cal} + \beta$$

Sensitivity loss
Depends on the residual wavefront PSD
+ stochastic

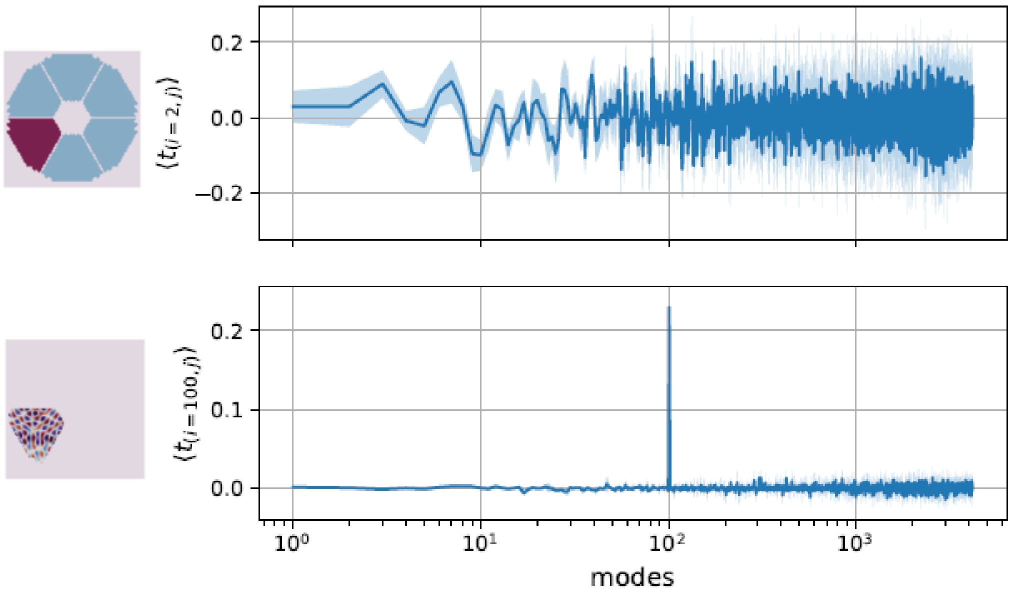
Bias
The measured differential piston when there is no piston in the WFE
Due to modal residuals + high order fitting

2. Pyramid wave-front sensor

2.3. From calibration to operation: the transfer matrix

$$rMat_{op} = \boldsymbol{T}^{-1} \cdot rMat_{cal}$$

- Non diagonal matrix for petals → modal confusion
  - *The pyramid measures petal when there's no petal*
- Unstable, even for a stable, fixed seeing value
  - *Coefficients of* $\boldsymbol{T}$ *vary following a normal distribution with* $\frac{\sigma}{\mu} \approx 30\%$
- Ill conditionned for $\text{seeing} > 1''$
  - *The petal sensitivity is completely lost*



T matrix coefficients for a petal mode and an intra petal mode

Sensitivity loss

$$\alpha_i = t_{i,i}$$

Korkiakoski 2008
Deo 2019
Chambouleyron 2020

Cross talk strength

$$c_i = \sqrt{\sum_j t_{j \neq i}^{\;2}}$$

2. Pyramid wave-front sensor

2.3. From calibration to operation: the transfer matrix

$rMat_{op} = T^{-1}$

...onal matrix for petals → modal confusion

The pyramid measures petal when there's no petal

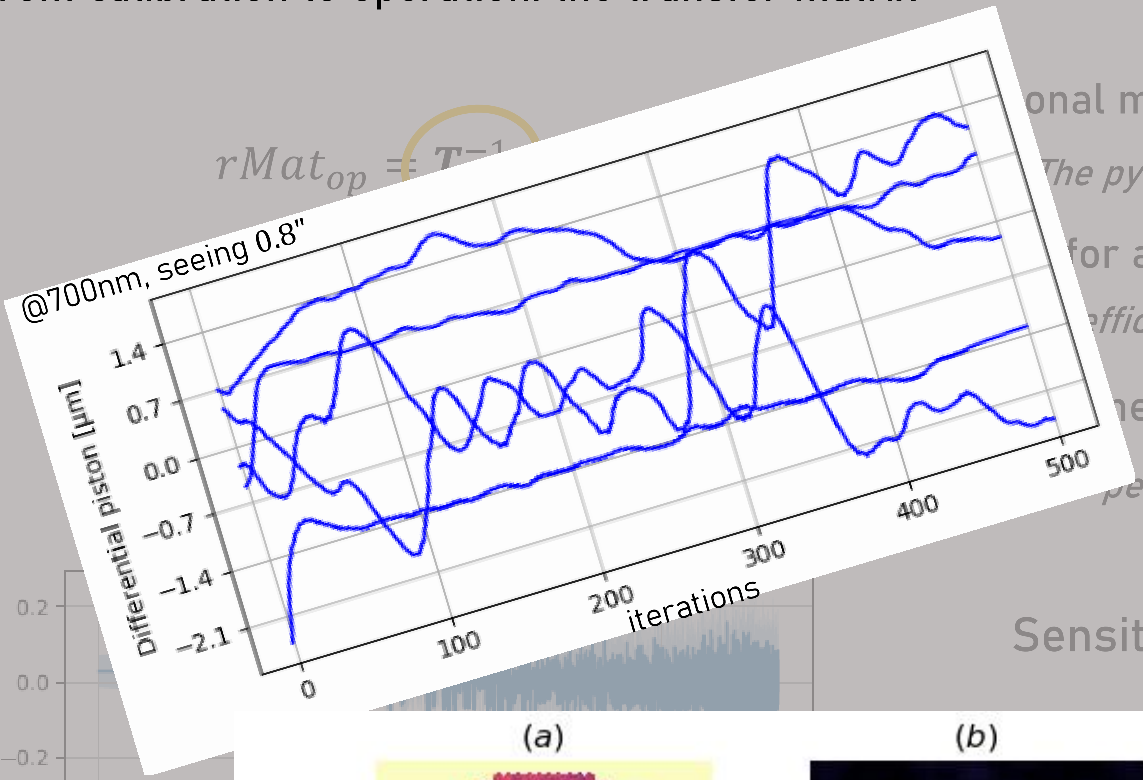
...for a same seeing

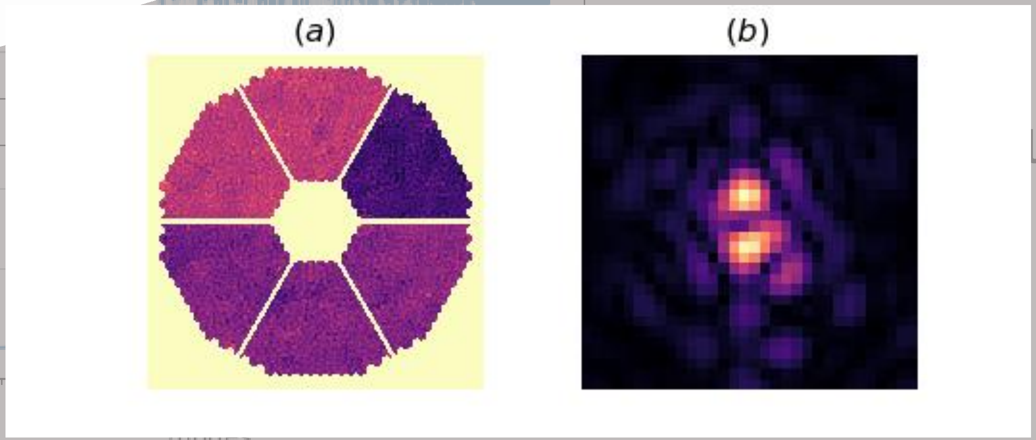
...fficients of T vary following a normal distribution with $\frac{\sigma}{\mu} \approx 30\%$

...ned for seeing $> 1"$

...petal sensitivity is completely lost

Random fluctuations of ΔP around values of λ_{WFS}





Sensitivity loss

$$\alpha_i = t_{i,i}$$

Korkiakoski 2008
Deo 2019
Chambouleyron 2020

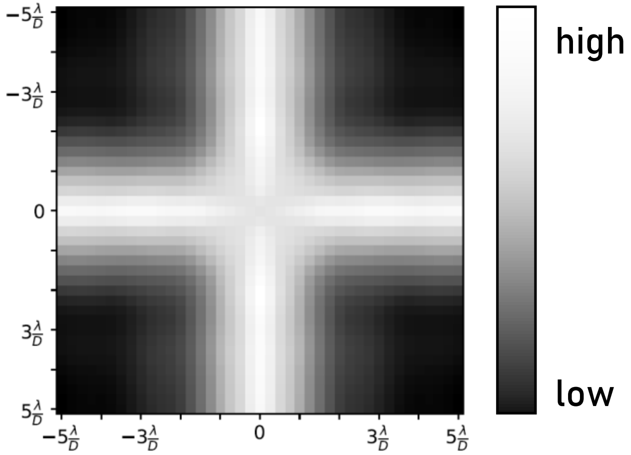
...ling

Island Effect in the wavefront residuals

Splitted PSF → Poor Strehl Ratio

$$c_i = \sqrt{\sum_j t_{j \neq i}}$$

3. Enhancing the pyramid sensitivity to differential piston



Pyramid sensitivity map to differential piston

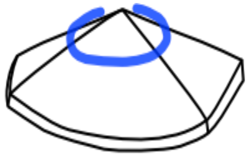
Fact:

Good sensitivity in the ***diffractive regions*** within $\pm\frac{\lambda}{D}$

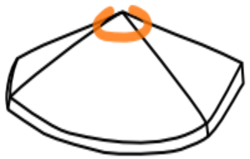
→ *Pyramid edges*

Spend more time on the edges

→ *Modulation paths*



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

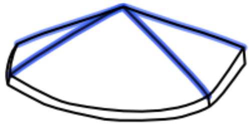


$a_{mod} = 1\frac{\lambda}{D}$

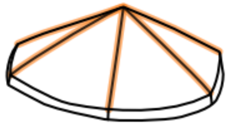
Clover

Add more edges

→ *Number of faces*



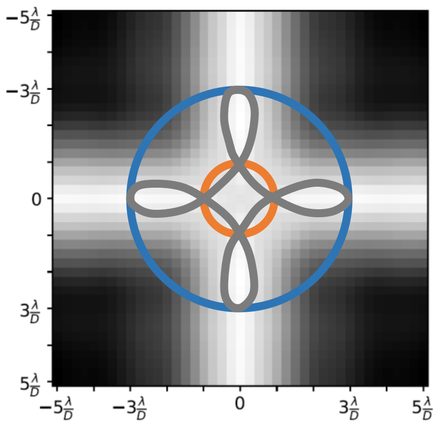
$4\ faces$

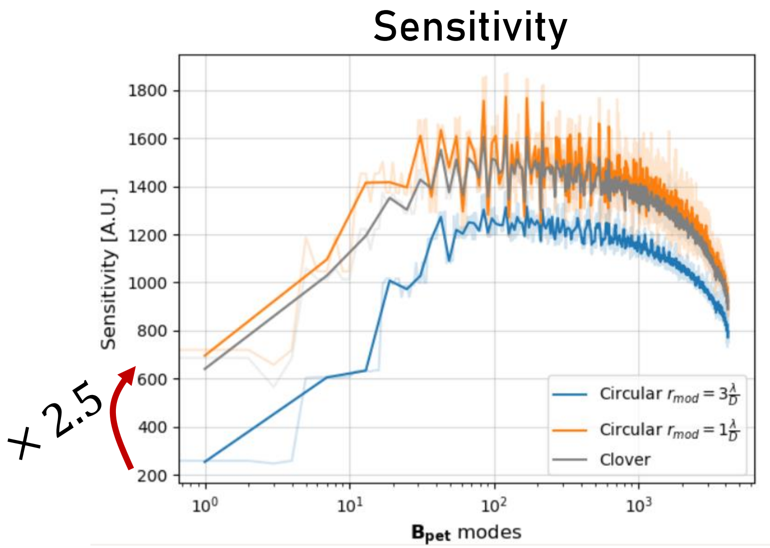


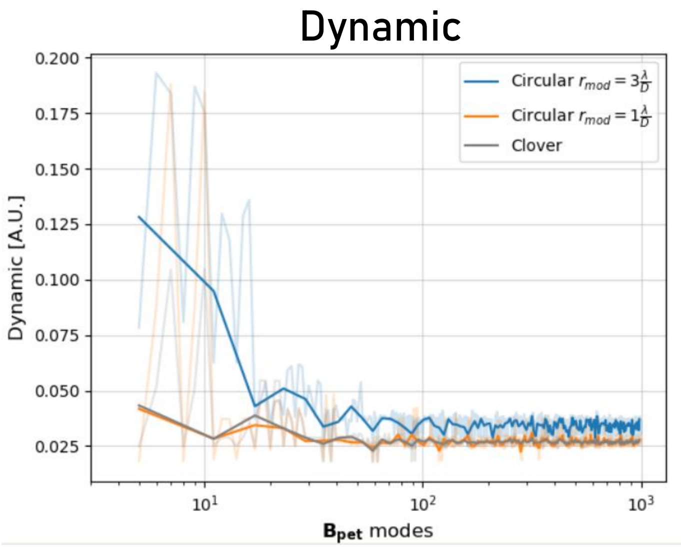
$6\ faces$

3. Enhancing the pyramid sensitivity to differential piston

3.1. Modulation path

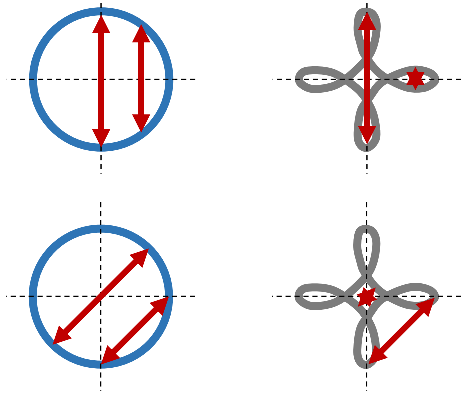






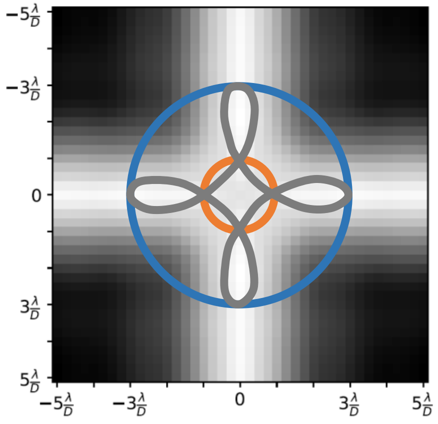
Gain in sensitivity … *At the cost of linearity*

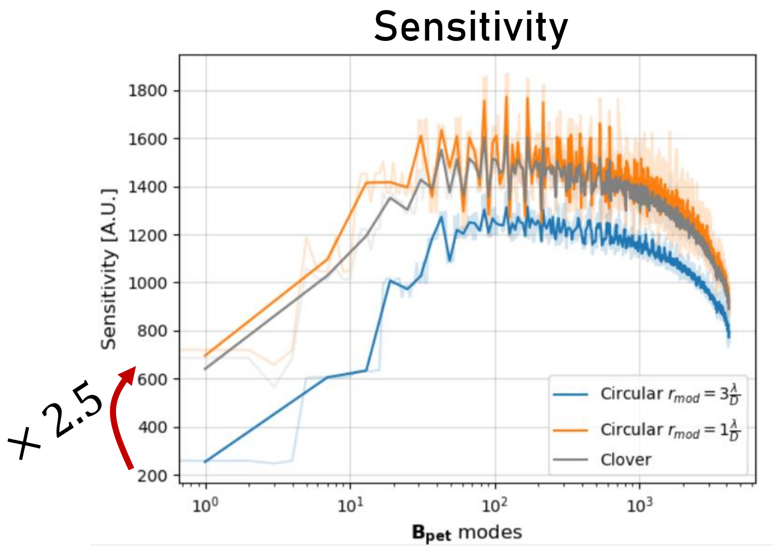
Trade-off with clover modulation?

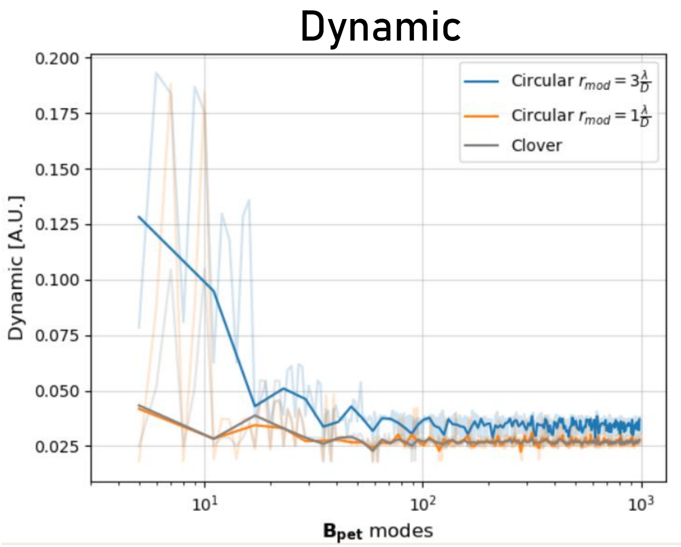


3. Enhancing the pyramid sensitivity to differential piston

3.1. Modulation path







Gain in sensitivity … *At the cost of linearity*

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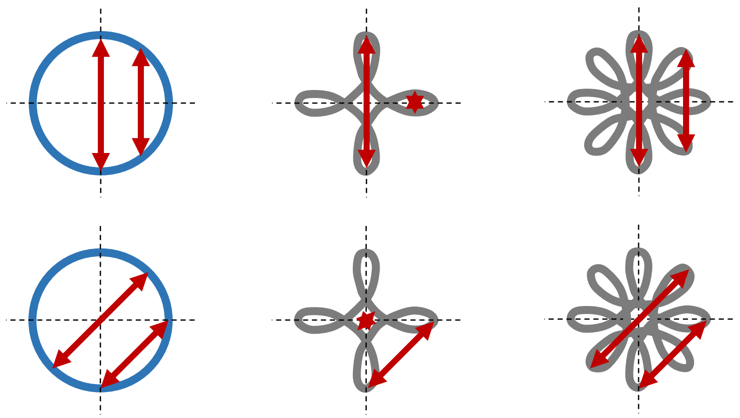


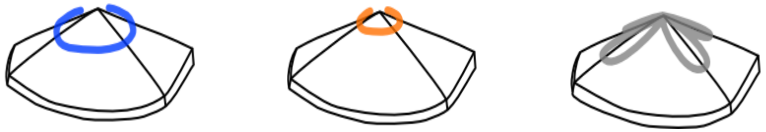
Gain of linearity

…

At the cost of ΔP sensitivity

3. Enhancing the pyramid sensitivity to differential piston

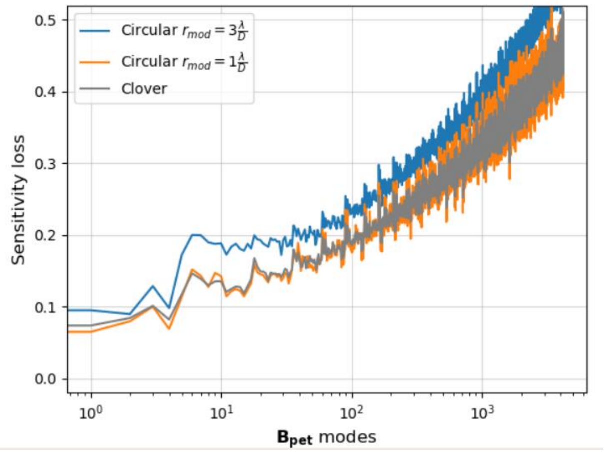
3.1. Modulation path

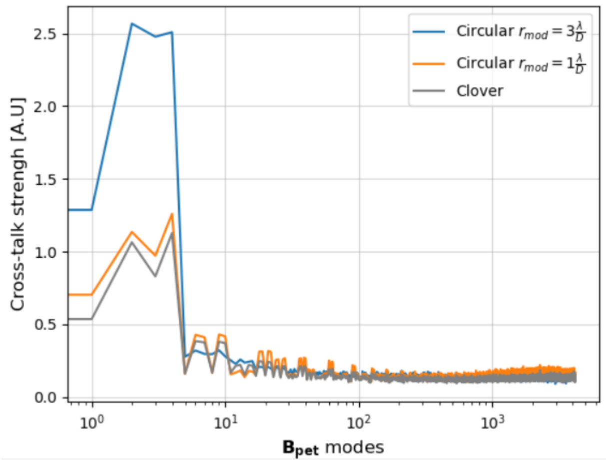


Sensitivity loss

Cross talk strength

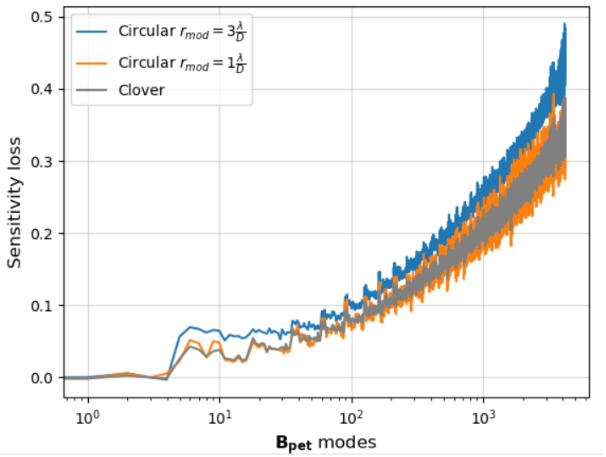
$seeing = 0.8"$

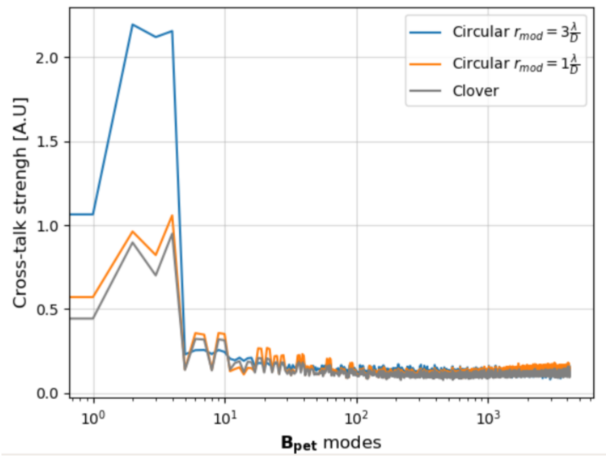




- Gain in the $\frac{sensitivity}{crosstalk}$ $ratio$

$seeing = 1.2"$

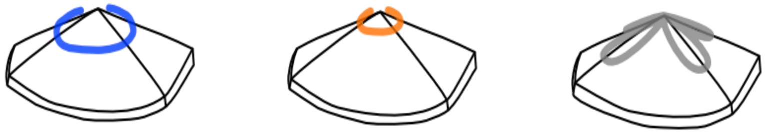




- Still dramatic ΔP sensitivity loss for bad seeing

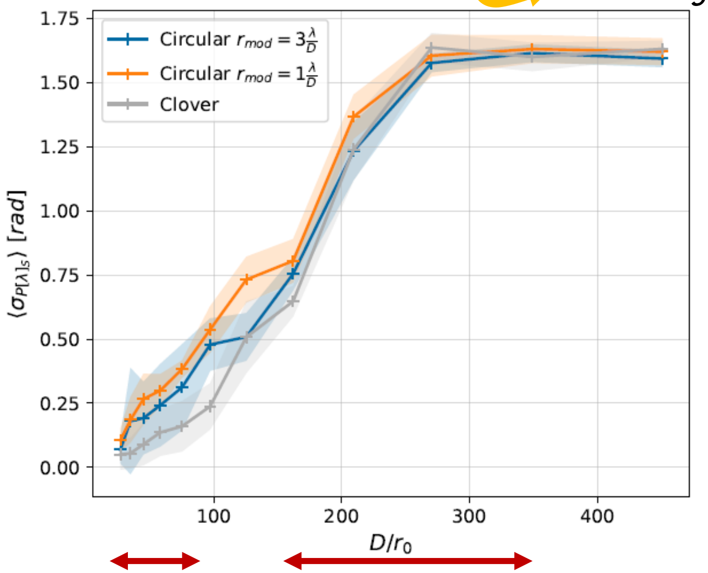
3. Enhancing the pyramid sensitivity to differential piston

3.1. Modulation path



Petal error

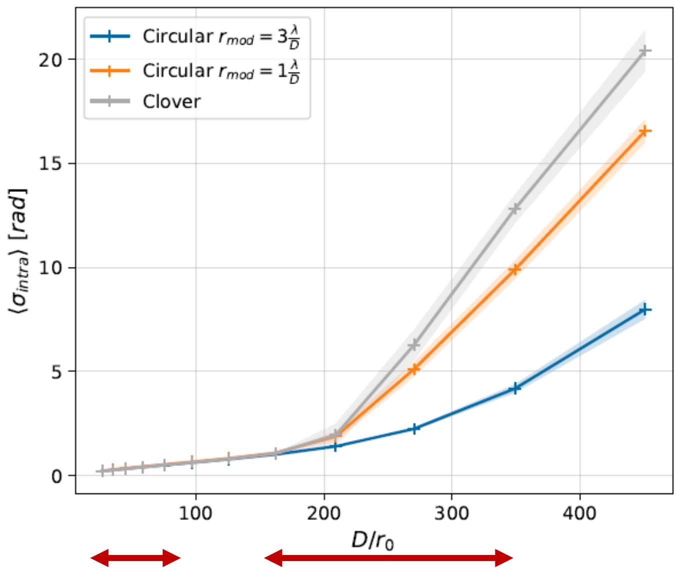
Modulo λ_{WFS} to set aside the wavelength ambiguity



ELT K-band Pyramid

ELT Optical Pyramid

Intra petal error



ELT K-band Pyramid

ELT Optical Pyramid

ELT Optical Pyramid

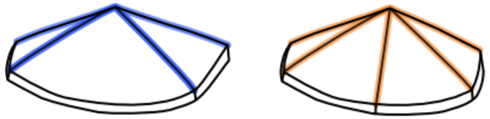
- Highly deteriorated intra petal residuals
- No ΔP sensing benefits in using clover modulation

ELT K-band Pyramid

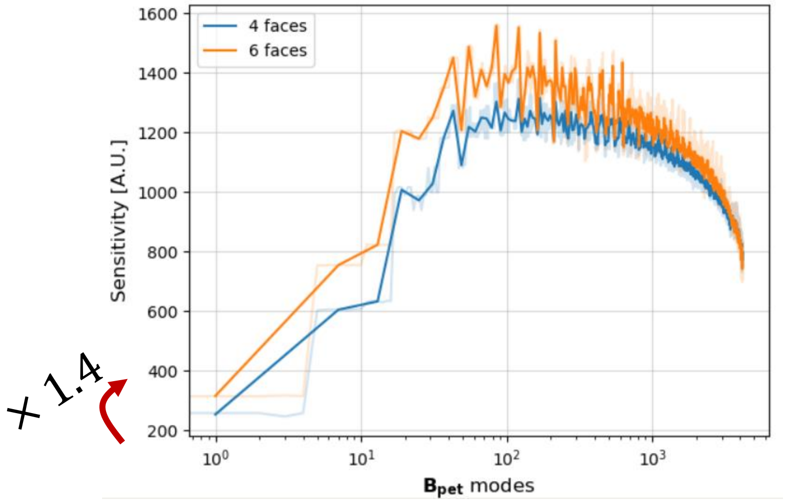
- Similar intra petal residuals
- Decrease of the ΔP error by a factor ≈ 2

3. Enhancing the pyramid sensitivity to differential piston

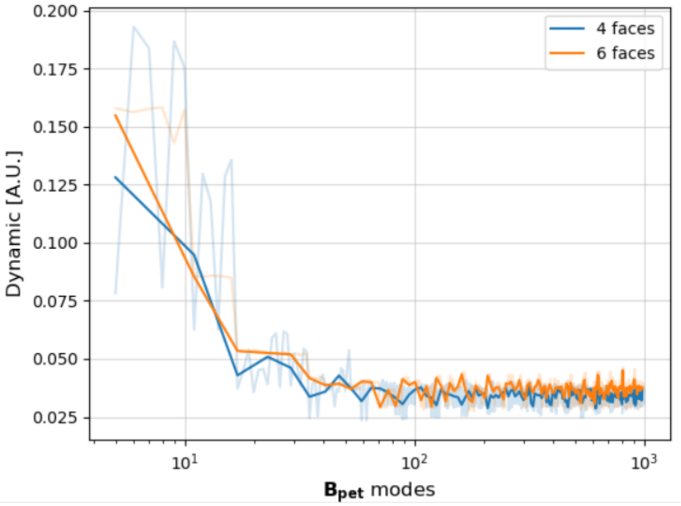
3.2. Number of edges



Sensitivity



Dynamic



Better petal / low order sensitivity

Unchanged dynamic

3. Enhancing the pyramid sensitivity to differential piston

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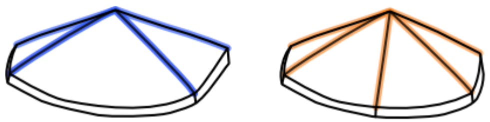
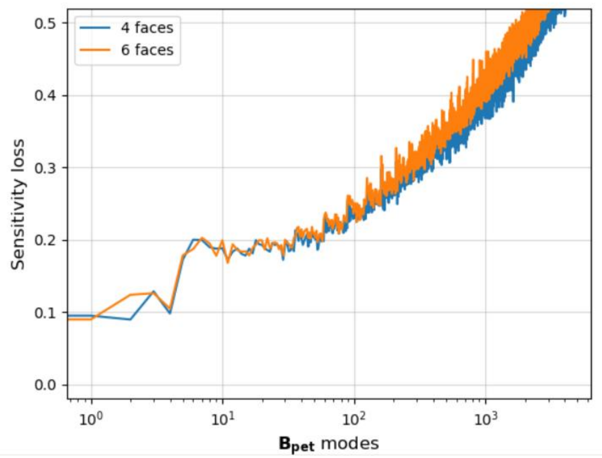
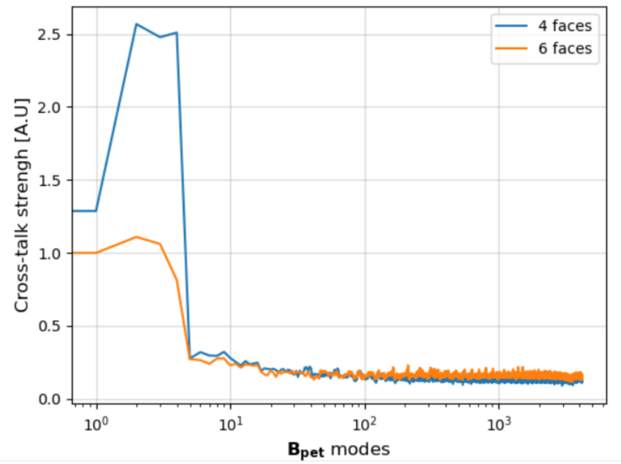


Sensitivity loss | **Cross talk strength**

$seeing = 0.8''$





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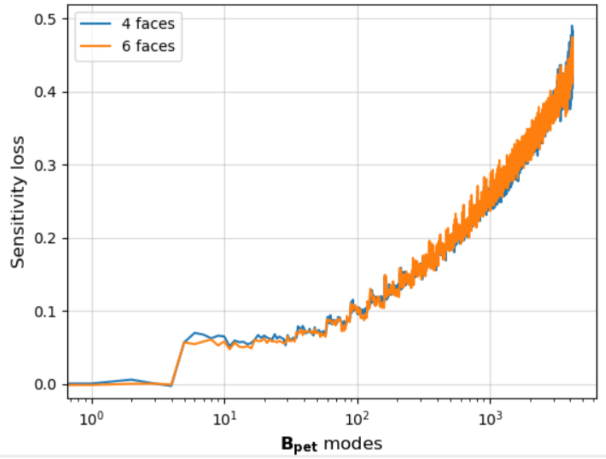

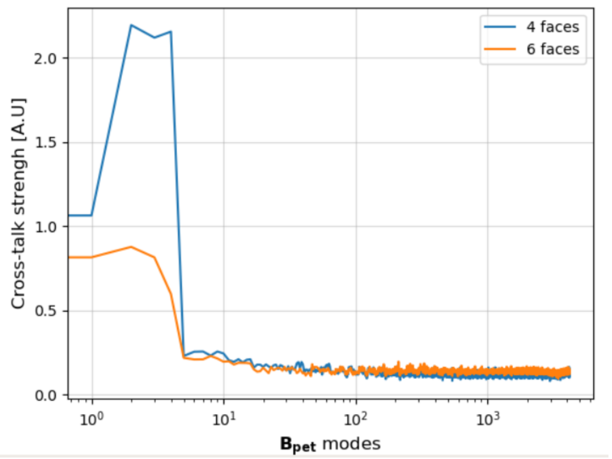

- Still dramatic loss in ΔP sensitivity for bad seeing

3. Enhancing the pyramid sensitivity to differential piston

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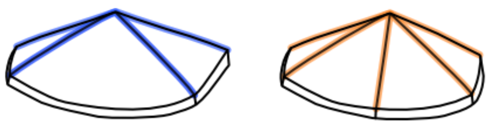

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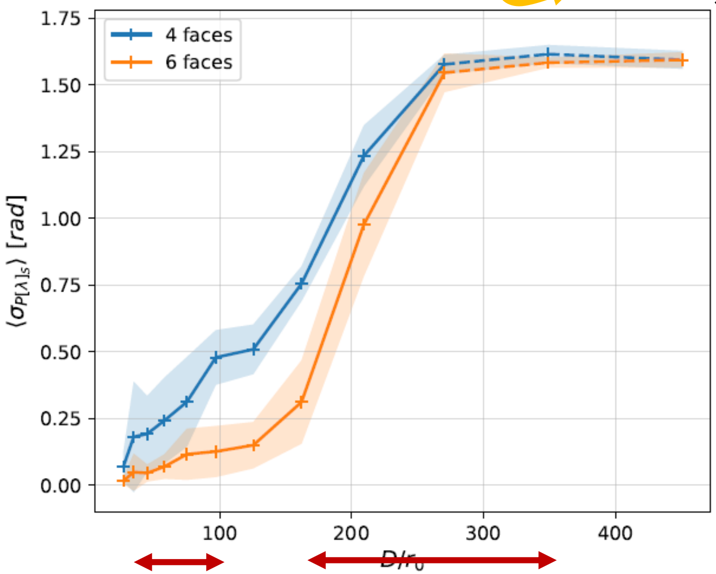

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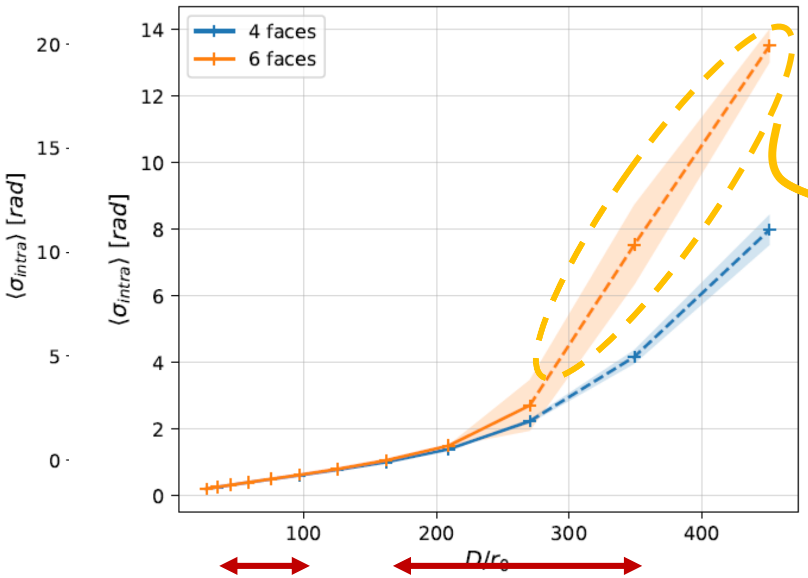
ELT Optical Pyramid

Intra petal error



ELT K-band Pyramid

ELT Optical Pyramid

/!\ Due to edges sampling

ELT Optical Pyramid

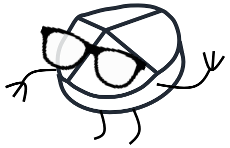
ELT K-band Pyramid

- Distinct decrease of the ΔP error

- Similar intra petal residuals

Better results expected with a higher number of edges
+ suitable sampling (not possible for now due to computation limits)

Conclusions



About differential piston measurement with the pyramid

For $seeing > 1\ arcsec$

The sensitivity to differential piston is lost

For $seeing < 1\ arcsec$

Poor sensitivity to differential piston

→ The petalling effect is driven by the **cross-talk** between differential piston and modal residuals + fitting

About the use of clovers

Trade-off between linearity and sensitivity → **Impossible trade-off** between petal sensing and intra petal sensing, both being related.

About increasing the number of edges

Provides a distinct improvement but it is a hardware solution

→ *Differential piston measurement with the pyramid wave-front sensor, in prep …*

Perspectives

→ Soft solutions to ensure the wave-front continuity

→ Additive hardware for low wind effect, … preferably in infrared

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