Strategy for sensing petal mode in presence of AO residual turbulence

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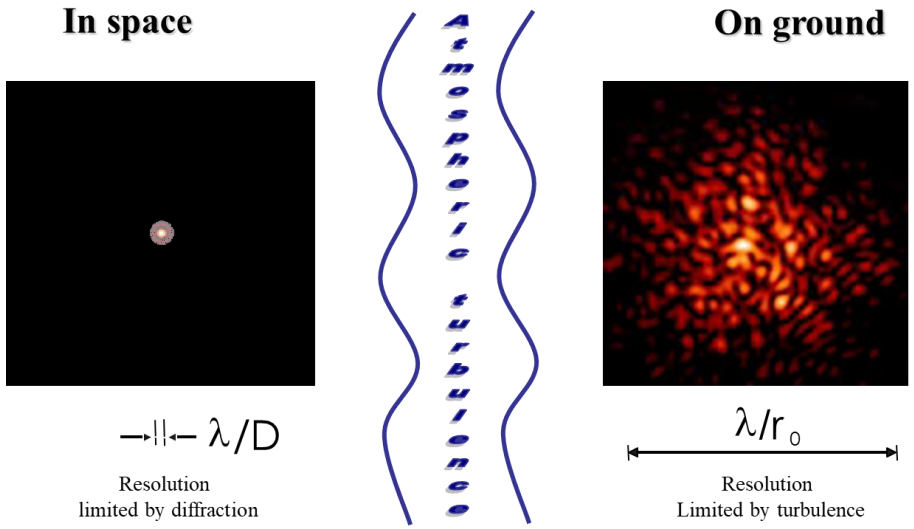
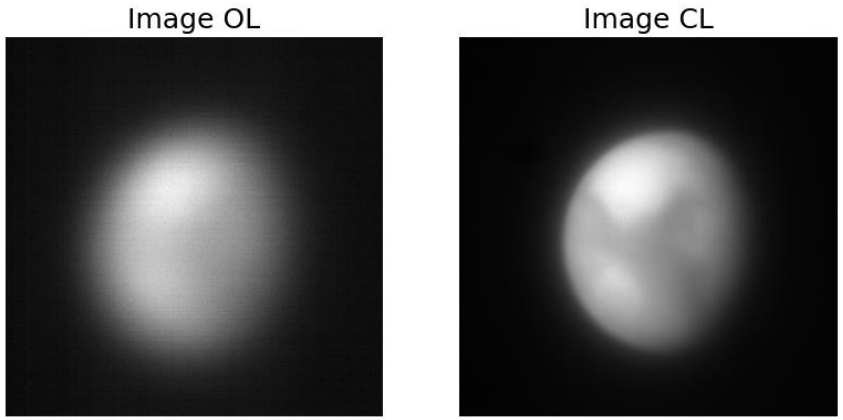
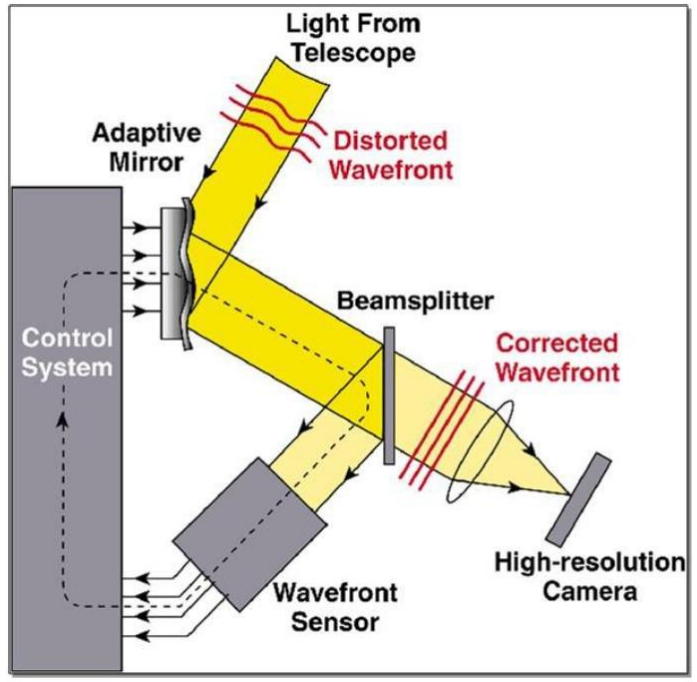
Adaptive Optics :





[Credit : Romain Fétick → PAPYRUS bench presentation Friday at 11:00]

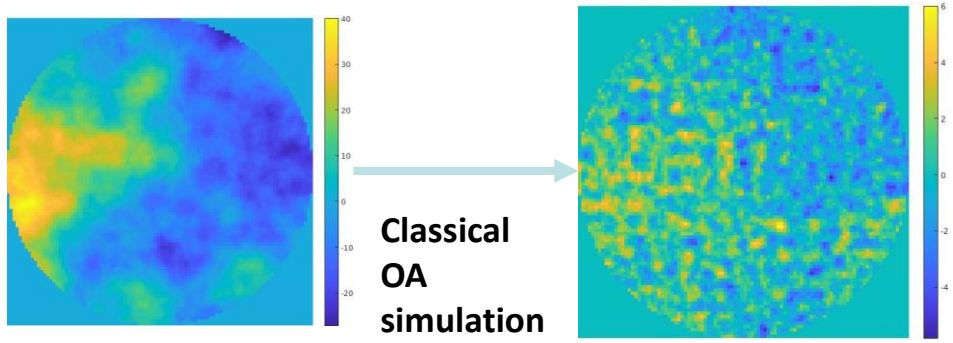


3 Main components

Wavefront sensor

Control system (real time computer)

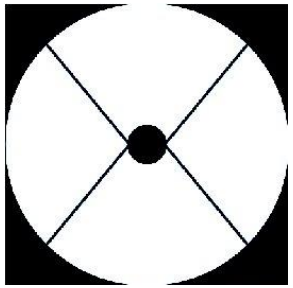
Deformable mirror



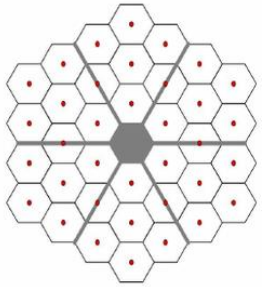
Classical OA simulation

Limited by :
- number of DM actuator
- Control loop speed
- Wavefront sensor reconstruction

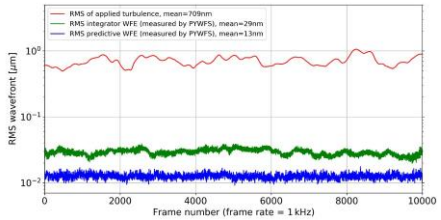
Adaptive Optics for giant telescope



Pupil VLT
spider=5cm

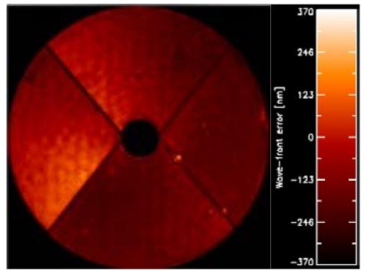


Pupil Keck
spider=2,5cm

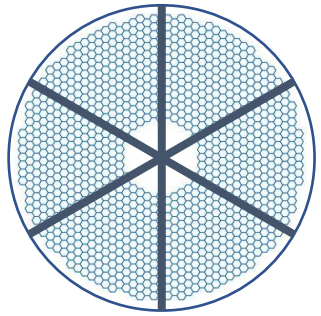


Credit : Rebecca Jensen-Clem

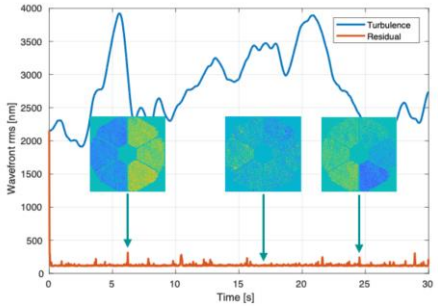
10m telescope (almost) not a problem for AO

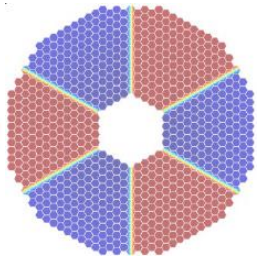


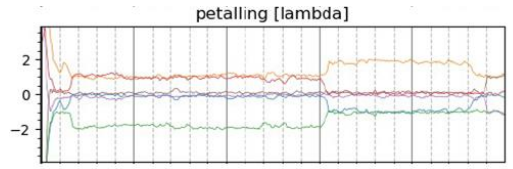
Credit : Jean François Sauvage



Pupil ELT
Spider = 50cm

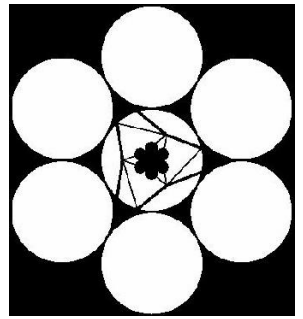




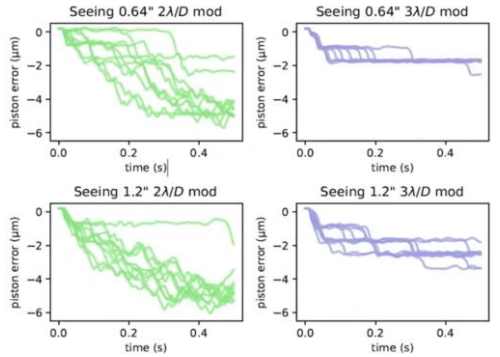


Credit : Charlotte Bond

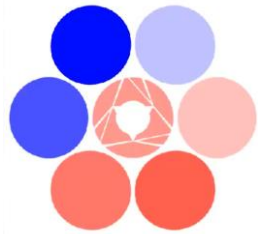
30m class → telescopes becomes a major problem



Pupil GMT
Spider >40cm



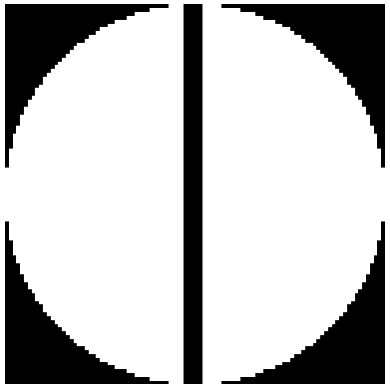
Credit : Sebastian Haffert



New challenge for wavefront reconstruction and control: phase gap → differential piston between pupil fragment → PSF limited by $D_{fragment}$

Our aim : reaching diffraction limit with a visible wavefront sensor

Modelisation of the problem : the toymodel

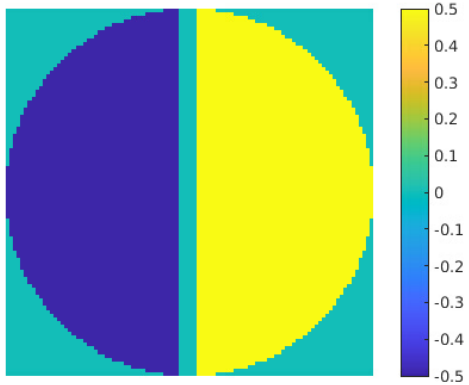


Toymodel pupil

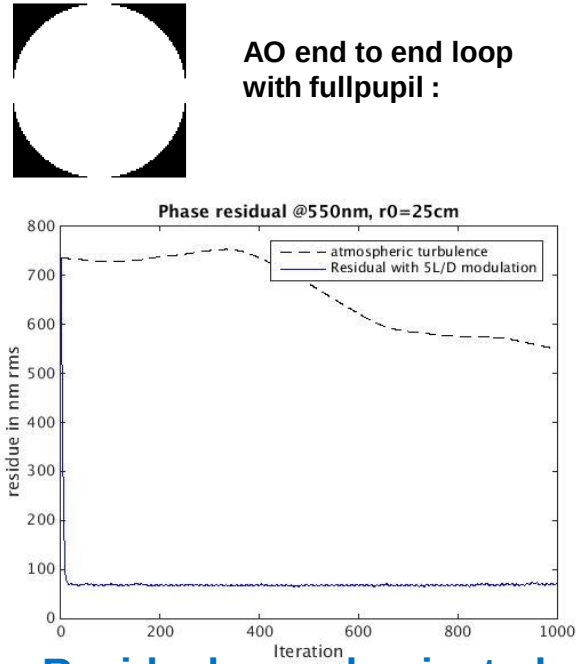
Only 2 fragment, 1 petal mode

Test setting : ELT size spider (50cm) on a VLT-class telescope(10m)
Spider represents 5% of pupil diameter

Conditions :
20*20 DM
D=10m
r_0=25cm @550nm
Wind speed=5m/s
No detector noise,
No sensor noise,
Sensing at λ = 550nm
F=500Hz
Spider size= 50cm
5λ/D pyramid for control

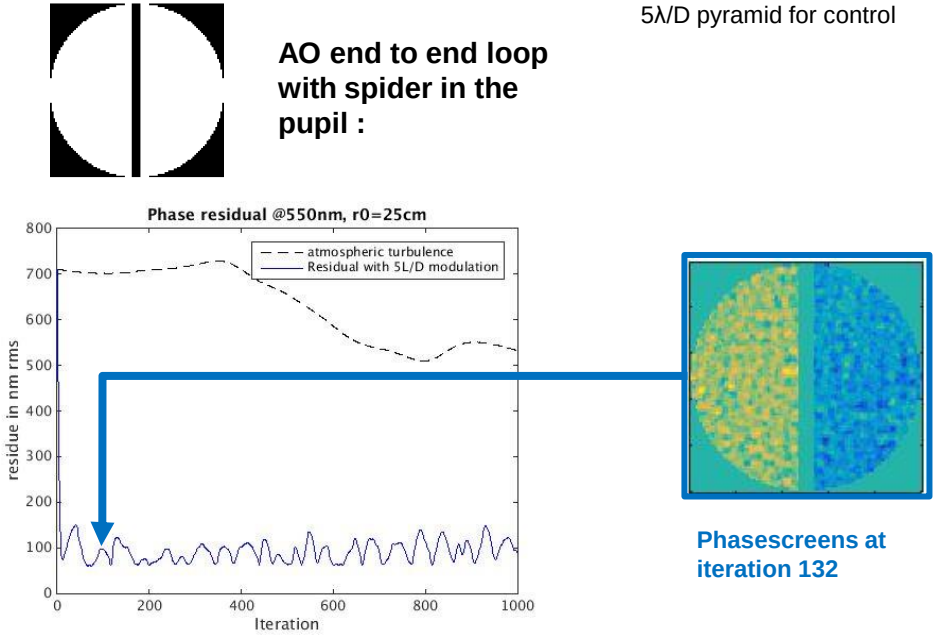


Petal mode



AO end to end loop with fullpupil :

Residuals are dominated by fitting error

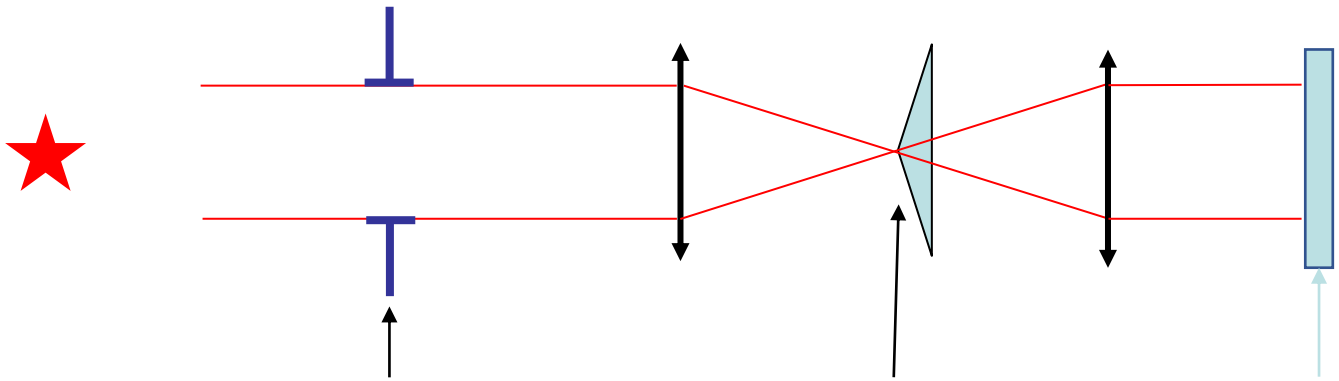


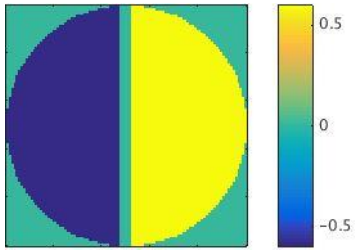
AO end to end loop with spider in the pupil :

Phasescreens at iteration 132

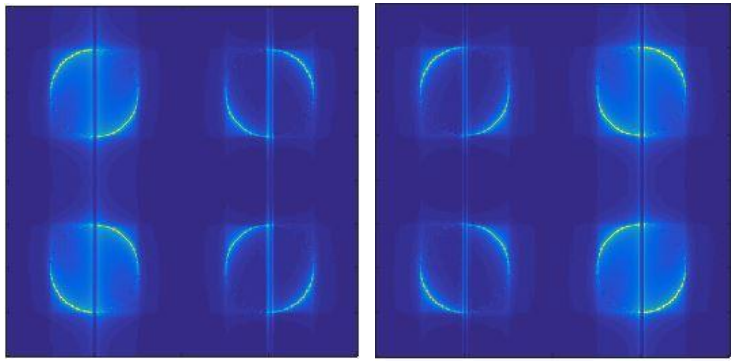
Residuals are fitting error + petal mode

Pyramid wavefront sensor



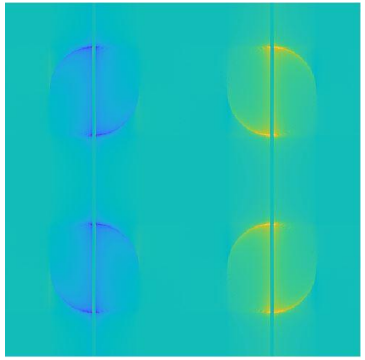


Petal mode 1*P



$I(a * petal)$ $I(-a * petal)$

$$\delta I(\varphi) = \frac{I(a*\varphi) - I(-a*\varphi)}{2 * a * F}$$

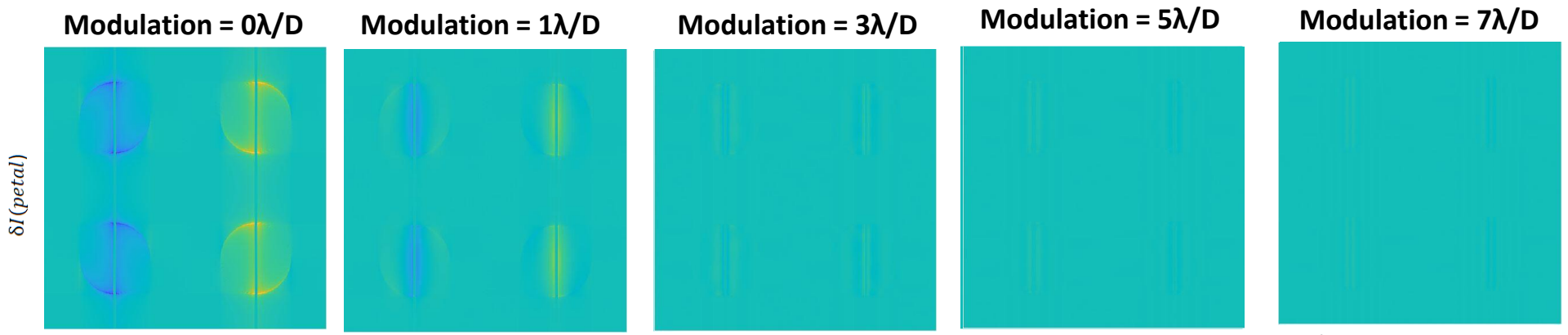


Flux $F = \sum_{all\ pixels\ on\ detector} I(0)$

Ref : R. Ragazzoni 1996 ***'Pupil plane wavefront sensing with an oscillating prism'***

Pyramid response to petal mode

Measure of sensitivity to petal mode : $S_{RON}(petal) = \|\delta I(petal)\|_2$ and $S_{\text{photon}}(petal) = \left\|\frac{\delta I(petal)}{\sqrt{I_0}}\right\|_2$



S_{RON}= 0,30
S_{photon}=0,80

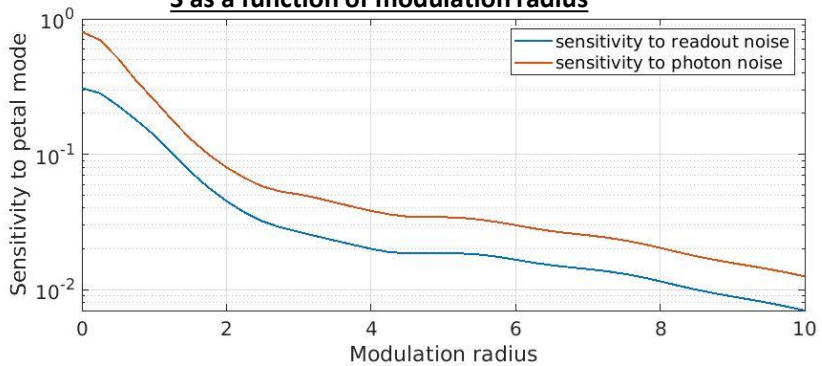
S_{RON}= 0,14
S_{photon}=0,25

S_{RON}= 0,027
S_{photon}=0,05

S_{RON}= 0,0019
S_{photon}=0,034

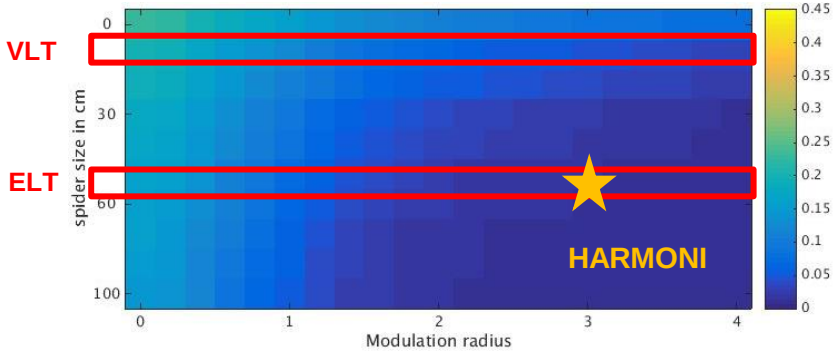
S_{RON}= 0,014
S_{photon}=0,025

S as a function of modulation radius



measure petal = unmodulated pyramid

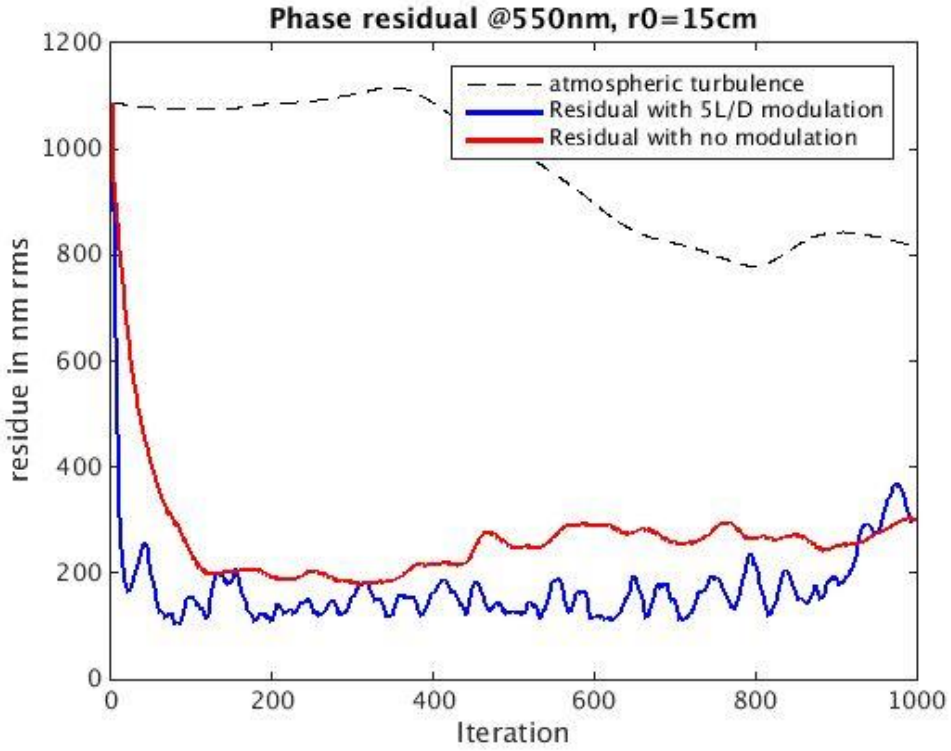
S_{RON} depending on modulation and spider size



Ref : V.Chambouleyron 2022 *'Optimizing Fourier-Filtering WFS to reach sensitivity close to the fundamental limit'*

Pyramid control without modulation

Conditions :
20*20 DM
D=10m
r_0 =15cm @550nm
Wind speed=5m/s
No detector noise,
No sensor noise,
Sensing at λ = 550nm
F=500Hz
Spider size= 50cm



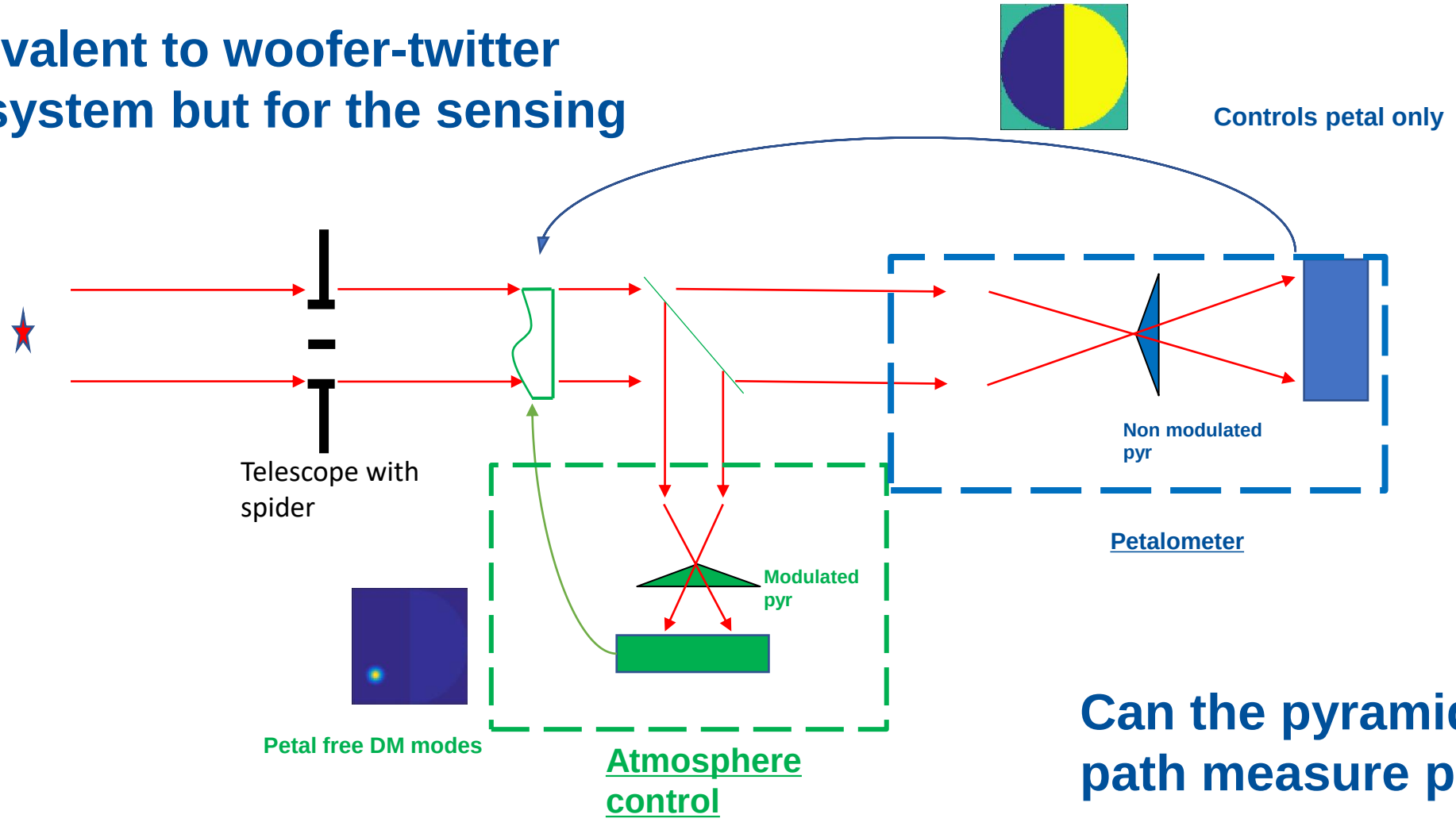
strong turbulence → need modulation → not sensitive to piston

Petal when modulating better than no modulation

Need two sensors,
1 for atmosphere
1 Petalometer

2 Path wavefront sensor

Equivalent to woofer-twitter AO system but for the sensing



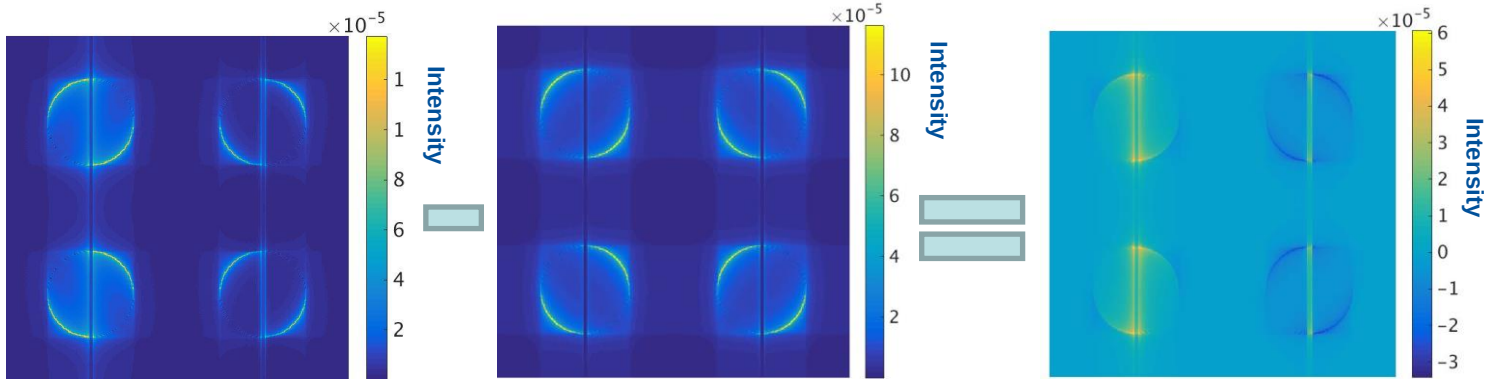
Can the pyramid in second path measure petal ?

Petal estimation

$$D = [\delta I(\varphi_1); \delta I(\varphi_2); \delta I(\varphi_3) \ \ldots]$$

$[\varphi_1, \varphi_2, \ldots] = Petal + 29\ first\ Zernike$

D **: interaction matrix**
$D^{\dagger}$ **: Reconstruction or control matrix**

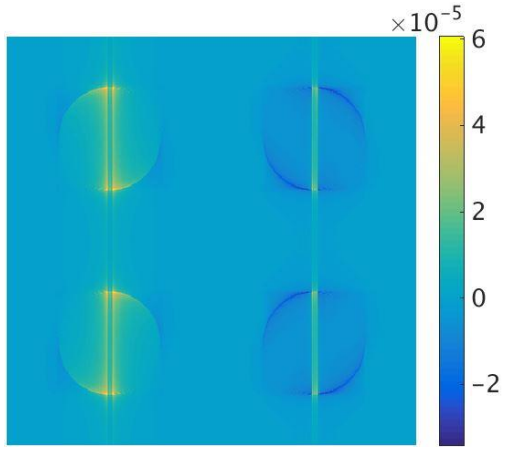


I(ϕ)/F **I(0)/F** $\Delta I(\varphi)$

$$\Delta I(\varphi) = \frac{I(\varphi) - I(0)}{F}$$

$$\hat{p}(\varphi) = D^{\dagger} \times \Delta I(\varphi)$$

$\hat{p}$ **Reconstructed petal**

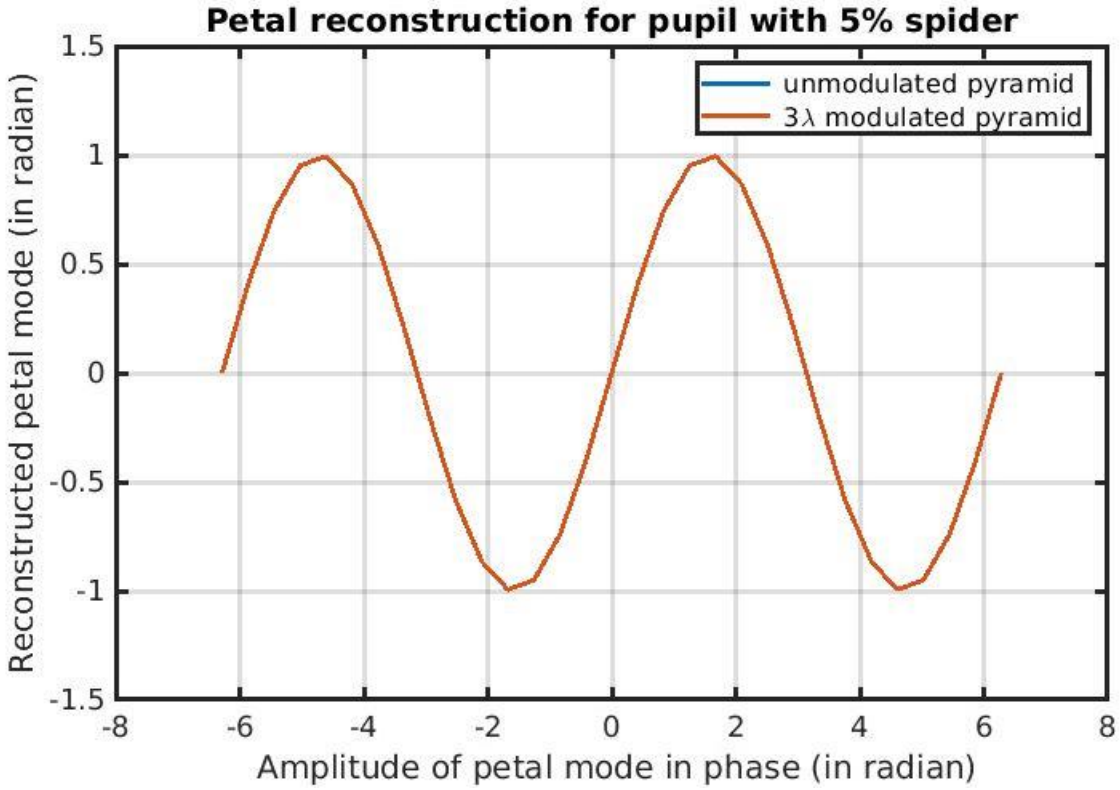


Introduced **p = - 0.1 rad**
Reconstructed $\hat{p}$ **= - 0.1 rad**

Goal : test $\hat{p}$ VS p in presence of residuals

Petal reconstruction : with no atmosphere

Estimate $\hat{p}$ for each $p \in [-2\pi\ , 2\pi]$

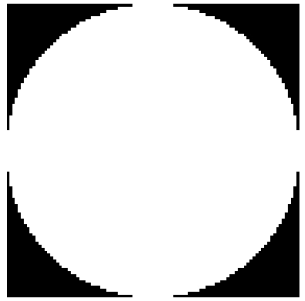


As expected, $\hat{p}$ = sin(p)

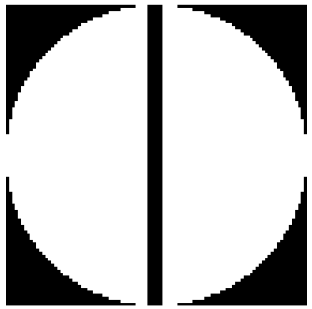
True for modulated and non modulated pyramid

Linearity curve in absence of noise or atmosphere

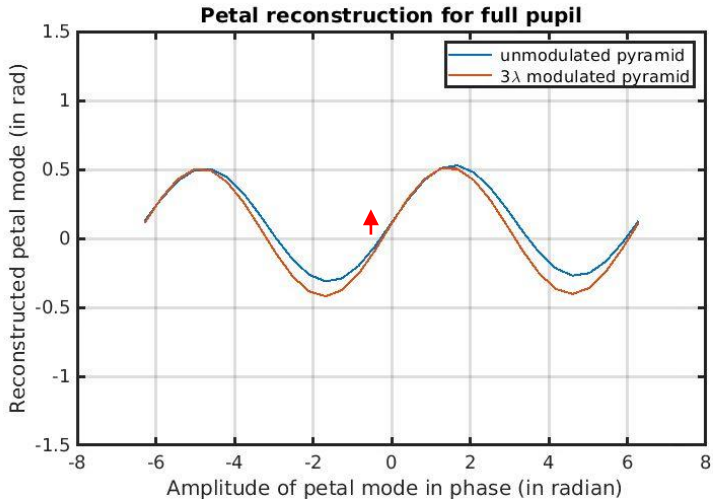
Petal reconstruction with 20x20 first stage residuals

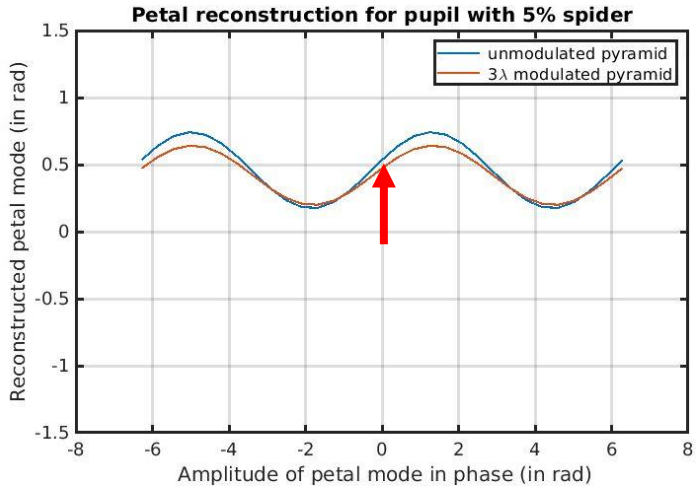


fullpupil



5% spider



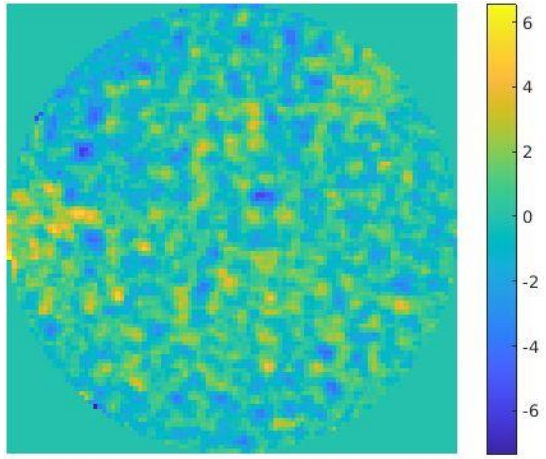


Bias no modulation = 0.45 rad

Bias modulation = 0.42 rad

Conditions :
20*20 DM
D=10m
r_0=15cm @550nm
Wind speed=5m/s
No detector noise,
No sensor noise,
Sensing at λ = 550nm
F=500Hz
Spider size= 50cm
Residual piston substracted from phasescreen

Residuals phase screen used :

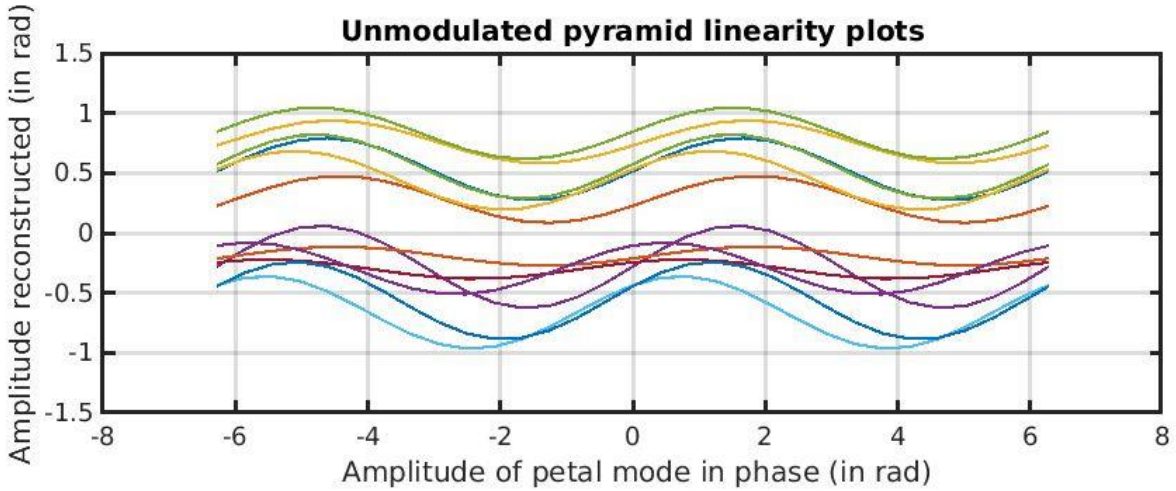


Bias > min of reconstruction
→ cannot reconstruct 0

Petal reconstruction is biased in presence of residuals and spider

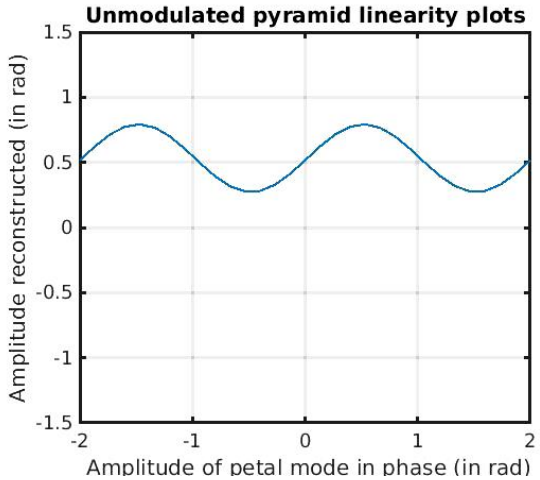
Petal reconstruction with variable residuals

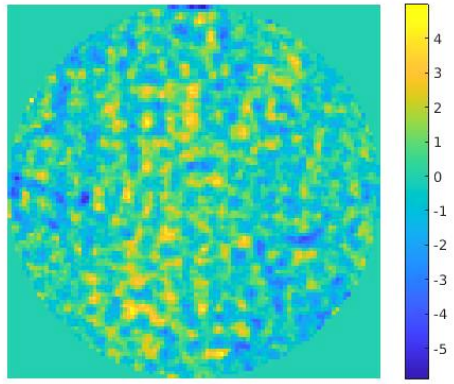
Reconstruction made for 10 independant residuals



Bias not repeatable

100 consecutive residual phasescreens

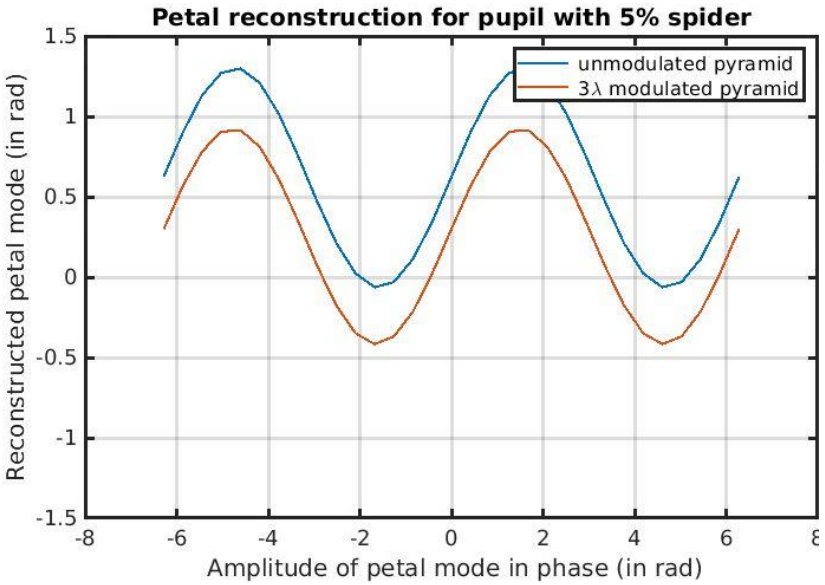




Highly depedant on phase residuals
Fast evolving

Petal reconstruction with variable residuals

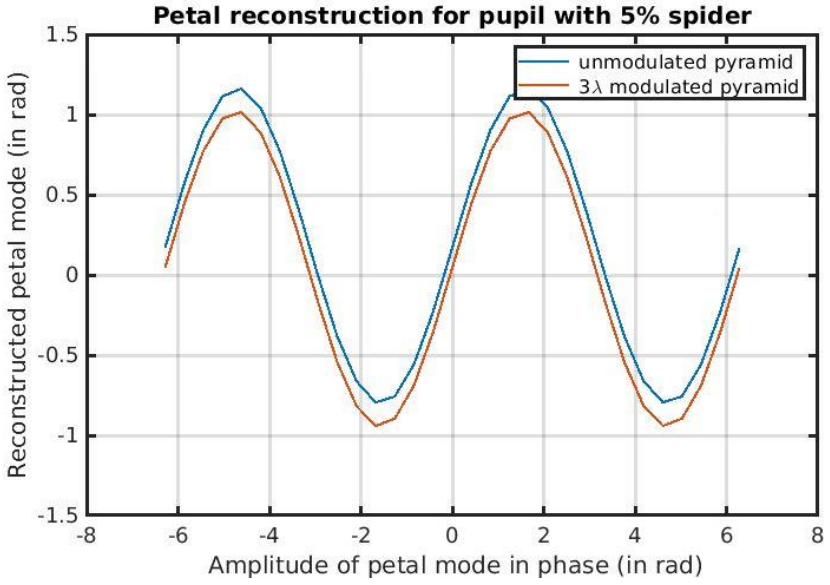
Residuals scaled by 0.5



Bias no modulation = 0.62 rad

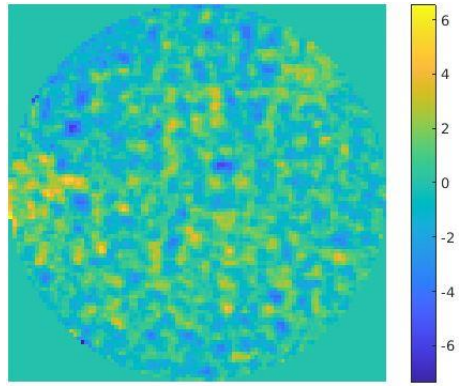
Bias modulation = 0.26 rad

Residuals scaled by 0.1



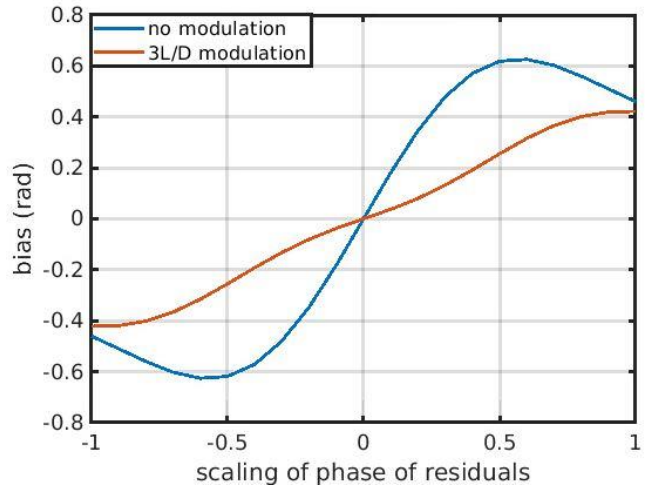
Bias no modulation = 0.18 rad

Bias modulation = 0.20 rad



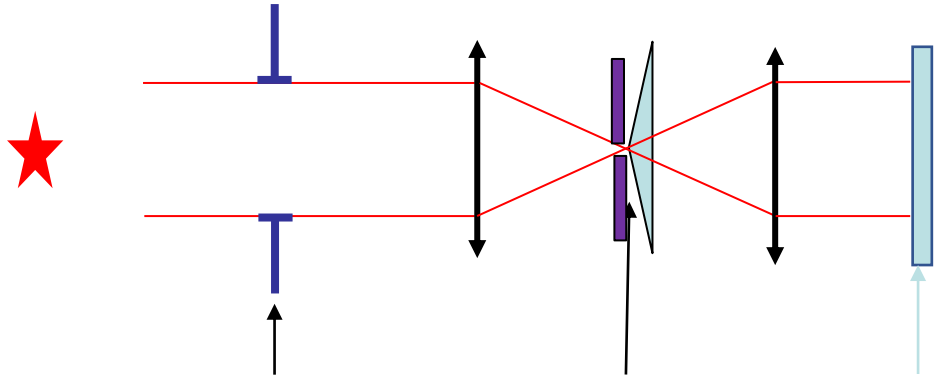
$s \in [-1\ 1]$

Petal bias for diferent scaling of residualphase



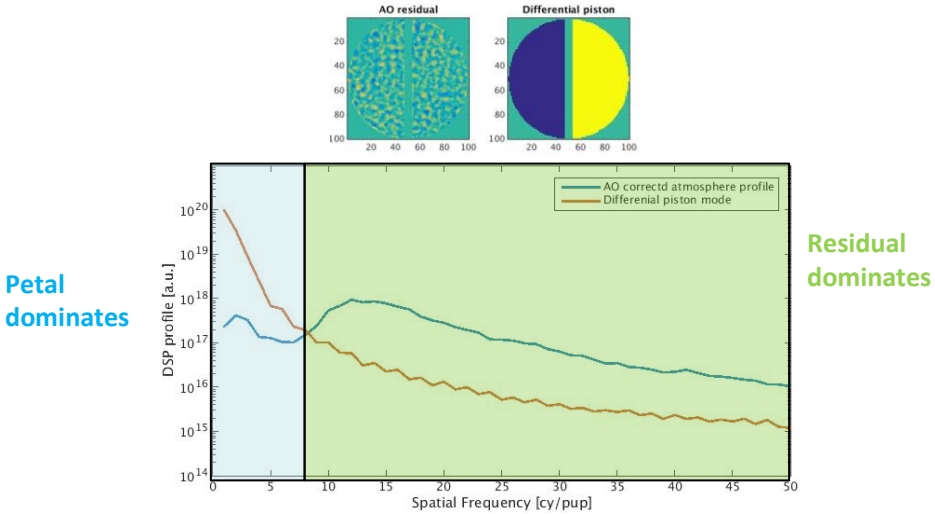
Bias is residual dependant → can't be controlled

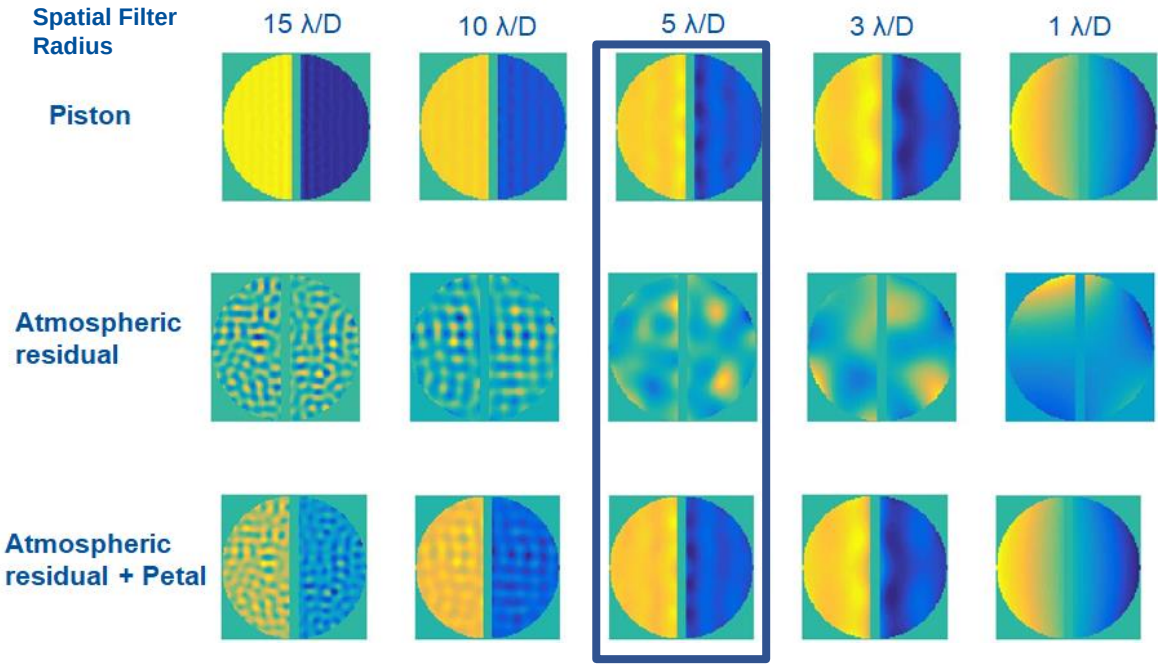
Reduce impact of residuals



Reduce the phase to be sensed → go to longer wavelength

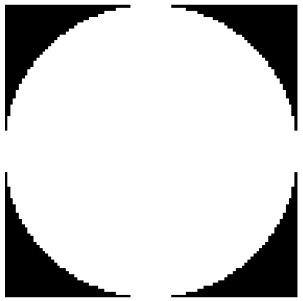
Reduce impact of residuals → spatial filter in the focal plane



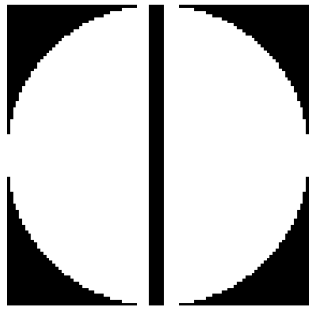


5 λ/D seems best compromise here

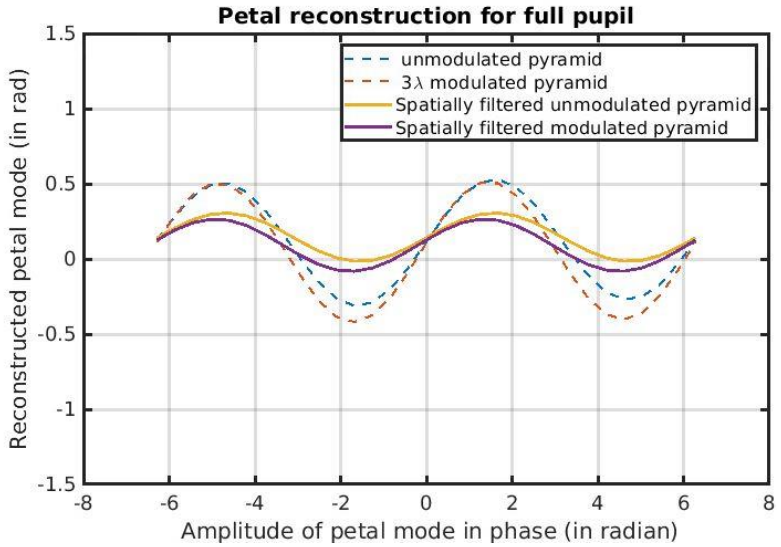
After spatial filtering linearity plots

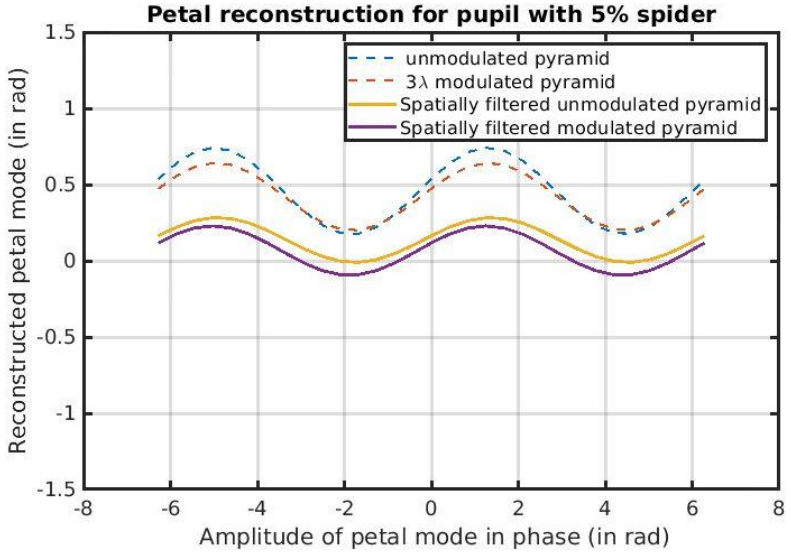


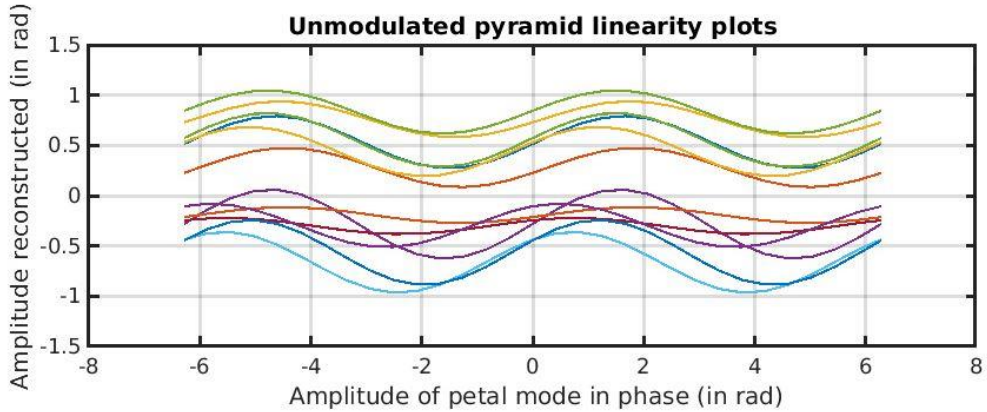
fullpupil

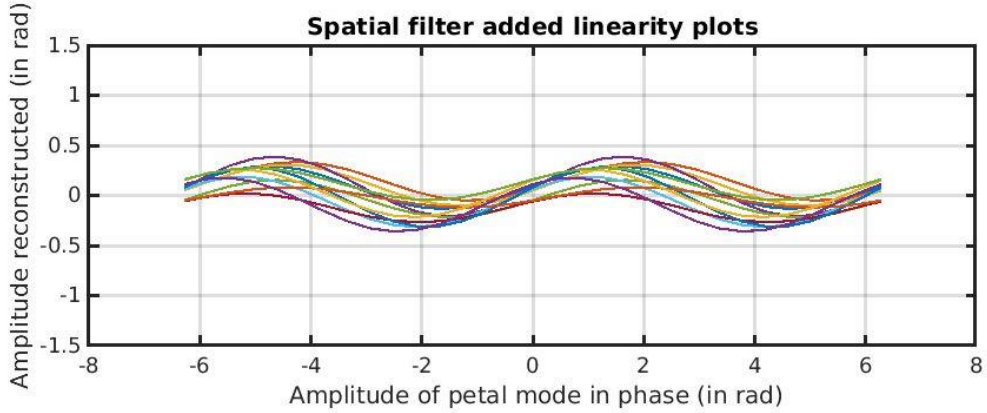


5% spider









Spatially filtered reconstruction is the same with or without spider
→Bias greatly reduced

Conclusion

- 2 sensor-system necessary to measure petal
- Residuals bias the petal measurement
- Spatial filter reduces this bias

Perspectives

Understanding origin of the bias → what creates bias in the residuals ?

Closed loop simulation → loss of light ? Size of spatial filter ? Best sensor ?

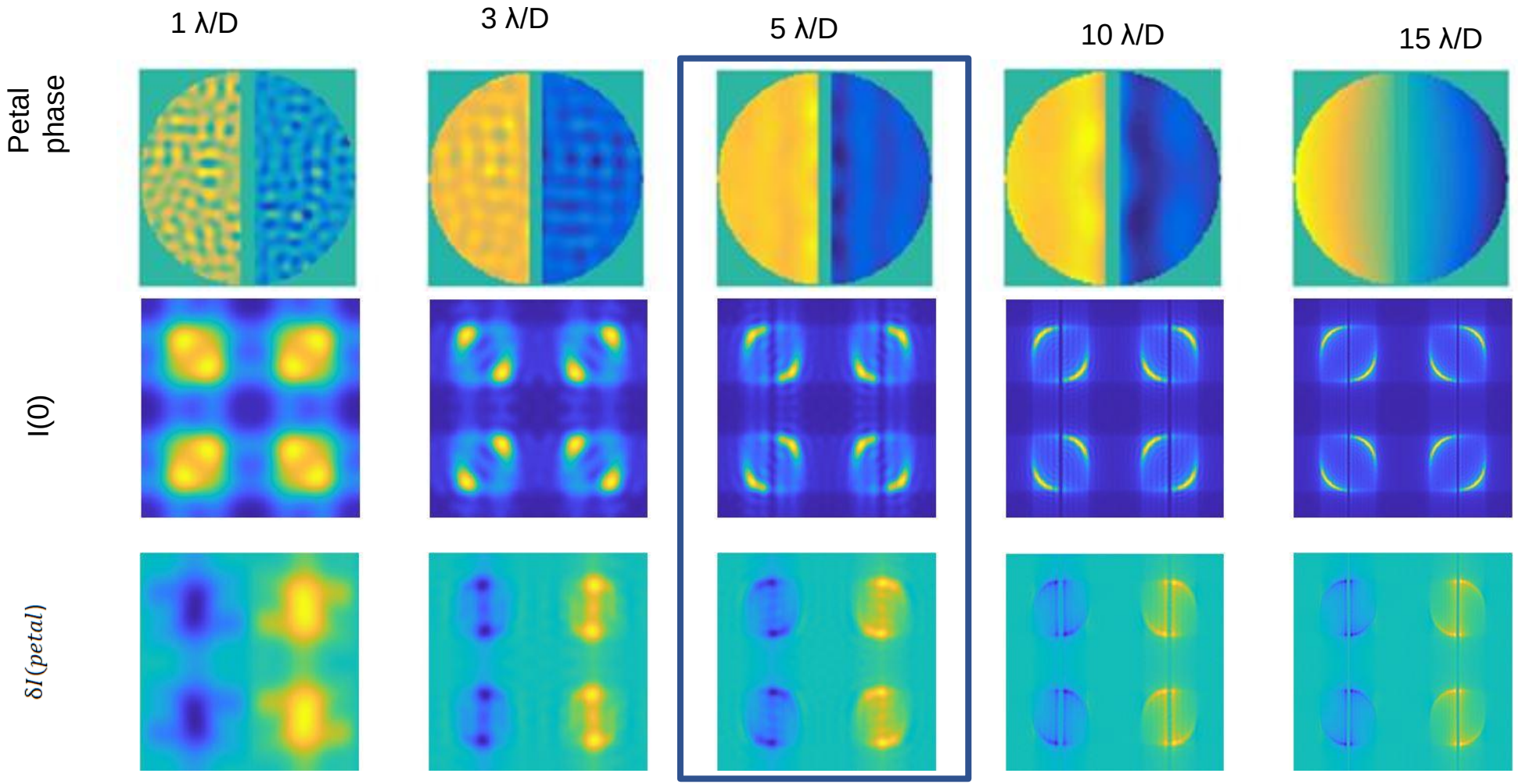
Simulation of ELT case

Spatial filter interest for other Fourrier Filtering WFS

Test on PAPYRUS ?

Thank you for listening !

Annex : Spatial filter effect on pyramid signal

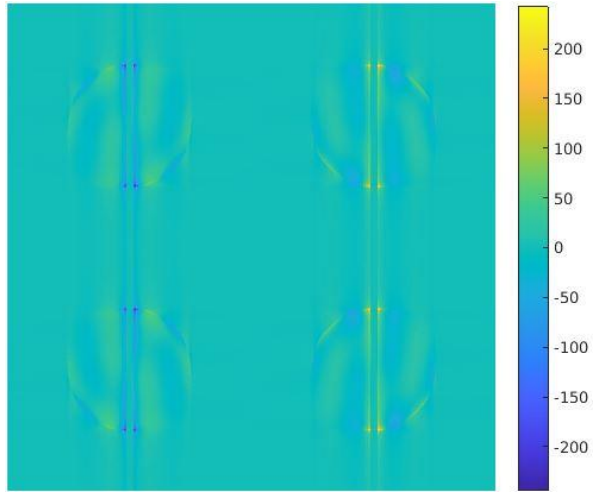


5 λ/D seems best compromise here

Annex Origin of the bias

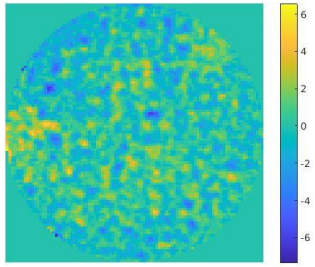
Look at $D^{\dagger}$ → what signal is used for petal reconstruction

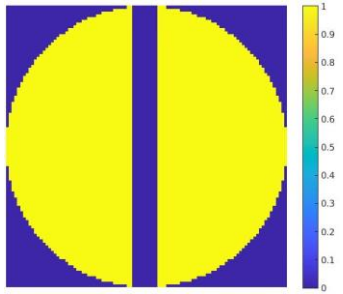
$D^{\dagger}$ of petal



Signal of petal reconstruction very close to spider
→ Residual next to spider causing bias ?

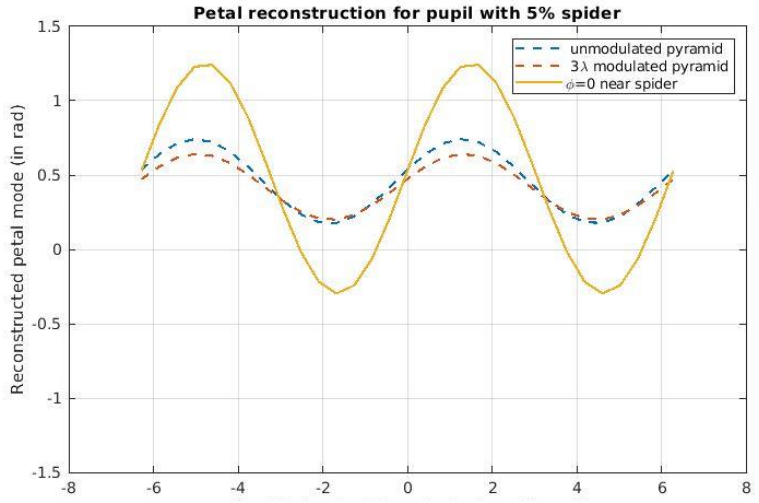
Blunt test : zero phase next to spider





Phase screen

As if Spider = 90cm

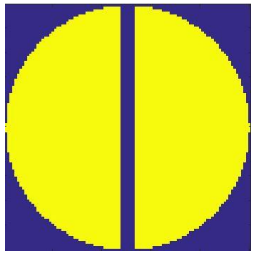


Origin of bias not understood

Comes from phase residuals

No effect on bias !

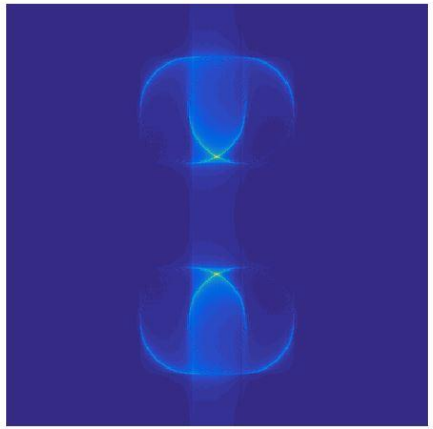
Annex : Improving sensitivity to petal



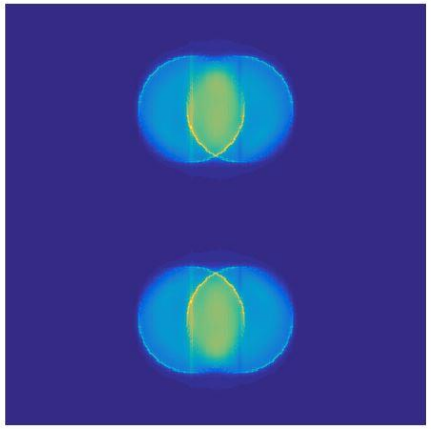
Toymodel pupil

No Spider

No modulation

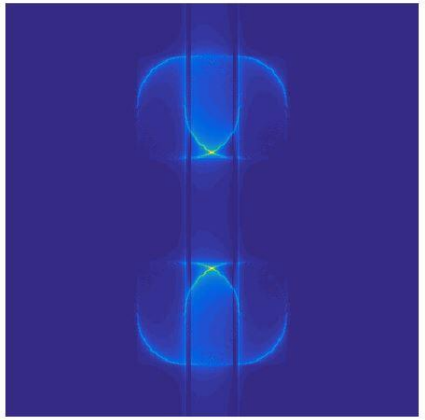


3 λ/D modulation

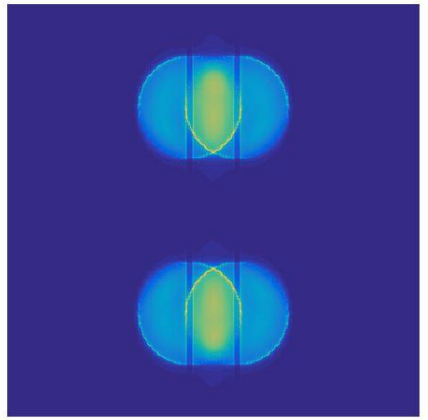


Spider

No modulation

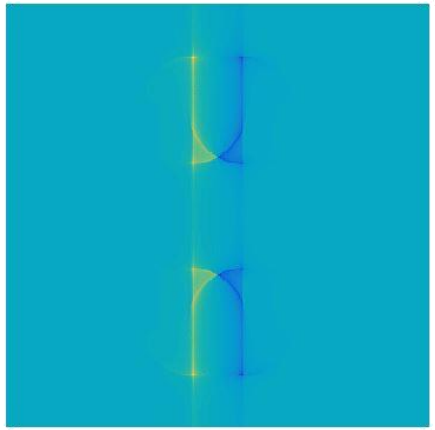


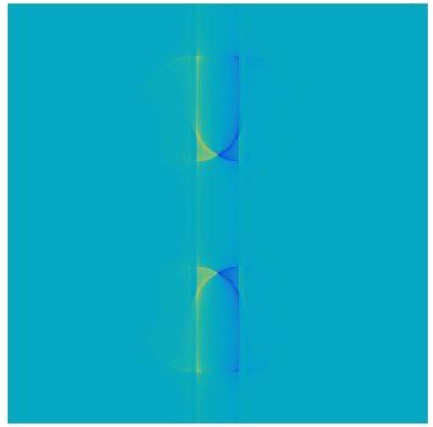
3 λ/D modulation

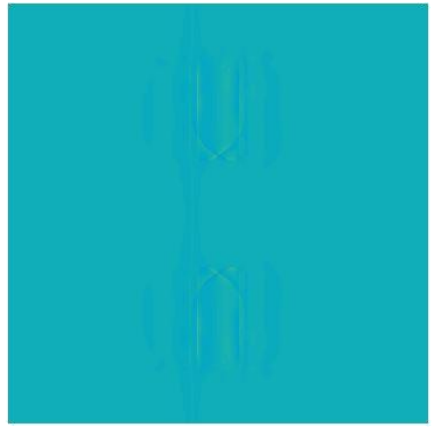


I ref

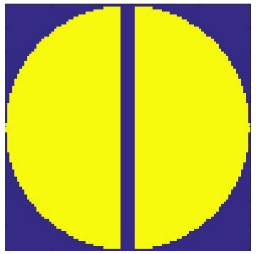
I piston





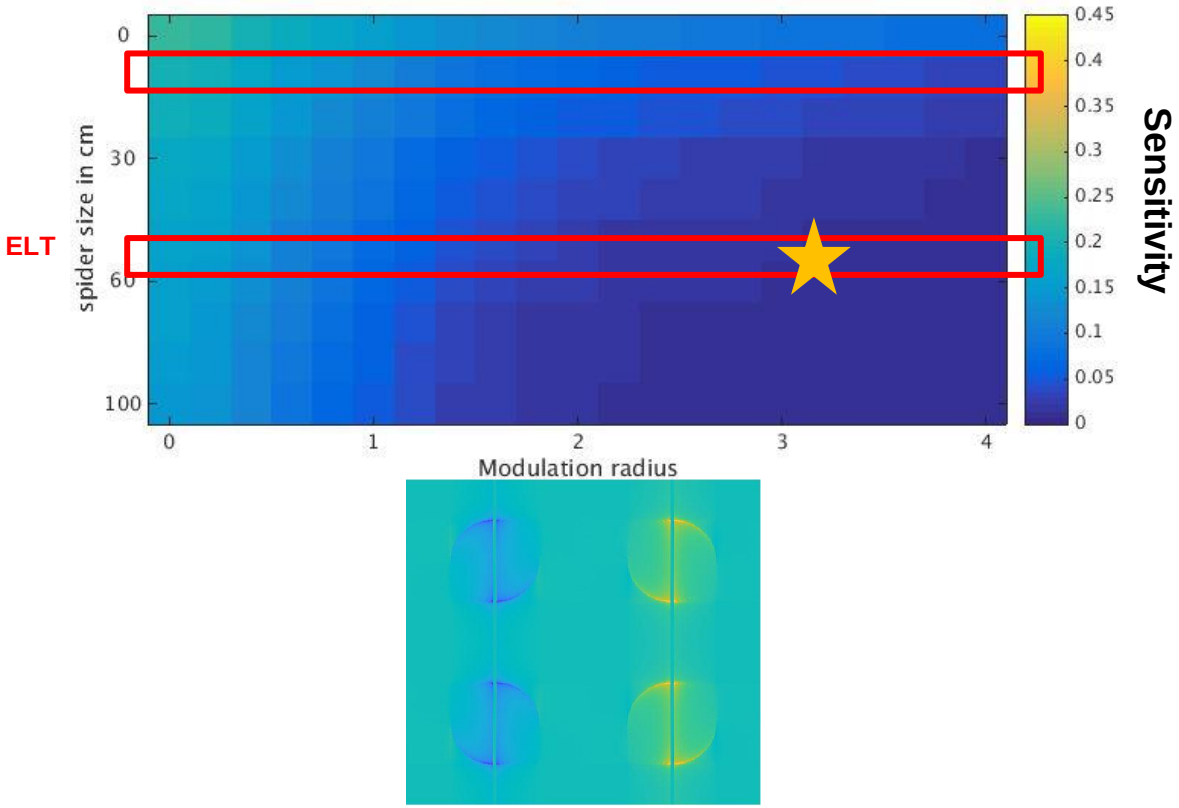


II Improving sensitivity to Petal : Loss with spider when modulating



Toymodel pupil (D=10m)

classic 4 sided pyramid



Asymetric pyramid