The Extreme Adaptive Optics test bench at CRAL based on Mach-Zehnder interferometer

Magali Loupias, Maud Langlois, E. Thiébaut, M. Tallon

XAO challenges

- **Strehl: 0.7<SR<0.9 [950nm-1750-nm]**
  - Large number actuators: **210x210= 3×10^4**

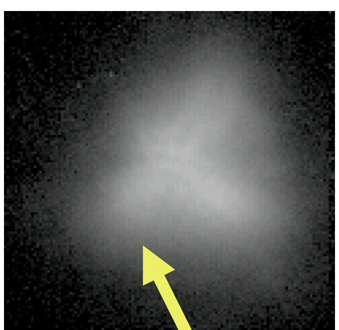
Maximize Signal

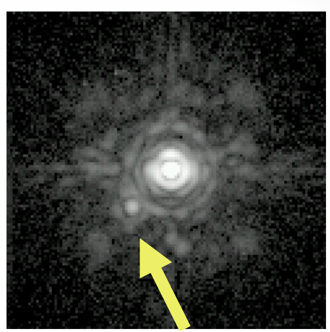
- **Reduce halo intensity 10^{-5} - 5×10^{-7} [20mas-700mas]**
  - Minimize residual phase errors at small spatial scales
  - Fast correction in close loop> **1 kHz**
  - Minimize noise propagation (WFS and optimal control)
  - Control chromaticity

Minimize Noise

- **Minimize quasi static aberrations : < 10-15nm (in AO band)**
  - Minimize/stabilize aberrations to reduce speckles effect
  - Control these aberrations with offsets the XAO loop
  - Reduce chromaticity (Optical design)

Control systematics





Error source	Nominal values
Seg. Piston and tip-tilt	36-nm rms
Seg. Mis-figure	72-nm rms
EELT 5 mirrors HF	sqrt(5) *20 nm rms
XAO static in band	10-nm rms
Reflectivity dispersion	1% rms

Wavefront sensors / ELT

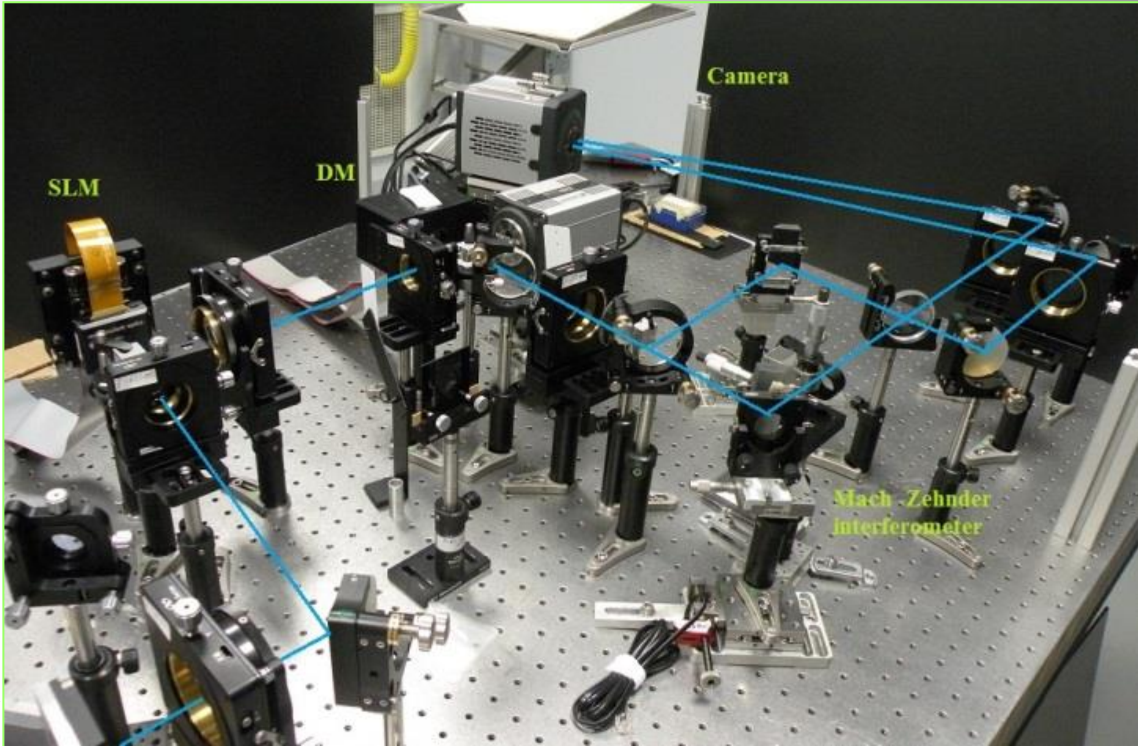
- **Sensitivity**
  - SHACK-HARTMANN / Slope measurement with important noise propagation for low and medium spatial scales
  - Optimum phase measurement methods with low noise propagation
    - PYRAMID (Ragazzoni)
    - MACH-ZEHNDER (Angel)
    - NON LINEAR CURVATURE SENSOR (Guyon)
- **Robustness**
  - SHACK-HARTMANN: Linear and high dynamical range: best for robustness
  - MACH-ZEHNDER: dynamical range limitation from phase ambiguity
  - PYRAMID with modulation
  - NON LINEAR CURVATURE SENSOR: Suitable but many iterations required
- **Fast Reconstruction**
  - SHACK-HARTMANN Sparse interaction matrix (FRIM, FFT control)
  - PYRAMID: non sparse matrix. Fourier control possible
  - MACH-ZEHNDER: Sparse matrix+ simple Model (FRIM control)
  - NON LINEAR CURVATURE SENSOR: FFT + large number of iterations

Set-up Objectives

- **R&D for future ELT instruments**
  - Test and optimise different configuration of the Mach-Zehnder WFS
  - Prove feasibility of XAO with E-ELT

- **Develop advanced control algorithms: (**Matrix-Vector multiplication not feasible). Close loop control for XAO (inverse approach, Fractal Iterative method, (and multi-lambda concept))

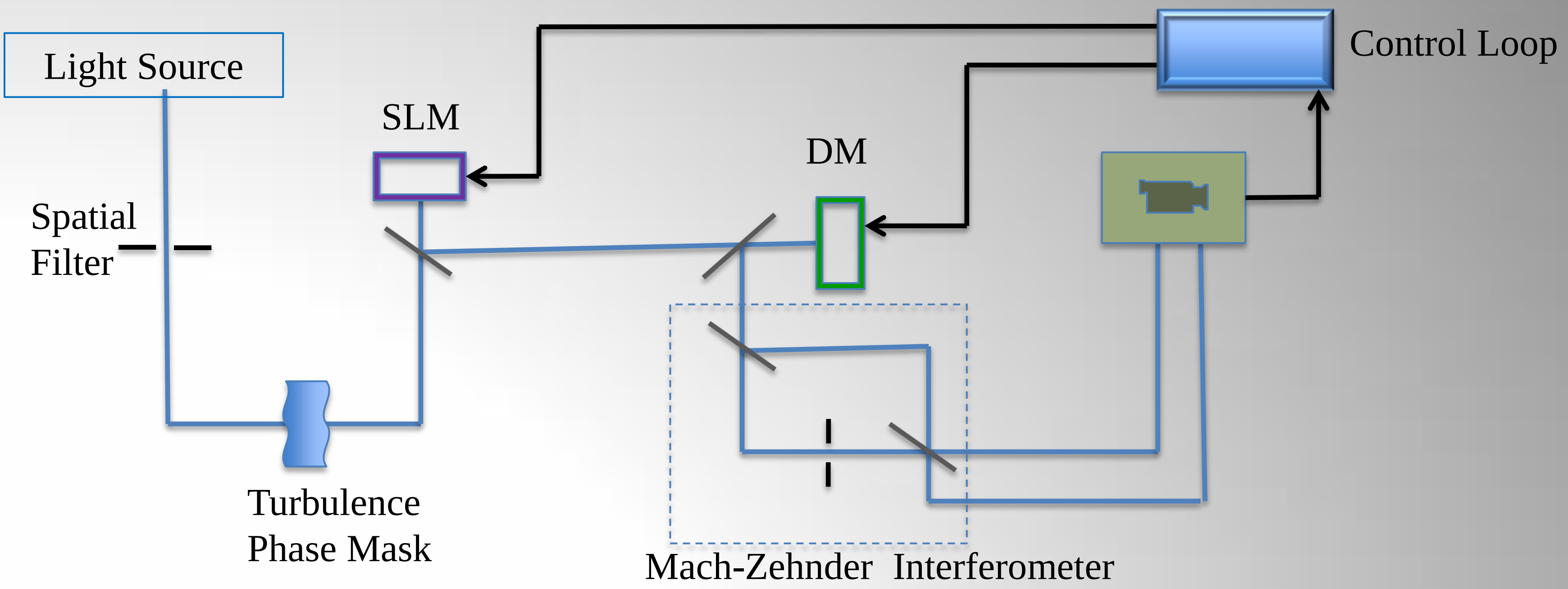
- **Integrate new high-contrast imaging techniques**
  e.g. phase-mask coronagraphs,
  apodisers, reflective Lyot-stop



XAO Set-up scales

System overview		
	XAO Setup scale	ELT scale
Mach-Zehnder wavefront sensor (MZWFS)		
Pupil spatial resolution	1200 pixels	3.5cm
Wavefront detection accuracy	Several nanometers (measured on bench) for P-V max = 600 nm	
Deformable Mirror (DM) corrector: woofer		
Pupil spatial resolution	12x12 actuators	2.9m
Wavefront correction dynamic	6 microns PTV	
Spatial Light Modulator (SLM) corrector: tweeter		
Pupil spatial resolution	512x512 pixels	7 cm
Wavefront correction accuracy	4 nanometer	
Turbulence phase screen		
Pupil spatial resolution	3000 pixels on diameter	1cm
Wavefront accuracy	~15 nanometer	
Control Loop		
Control frequency	~100Hz	>1kHZ (not on the bench)

XAO Bench Optical Setup



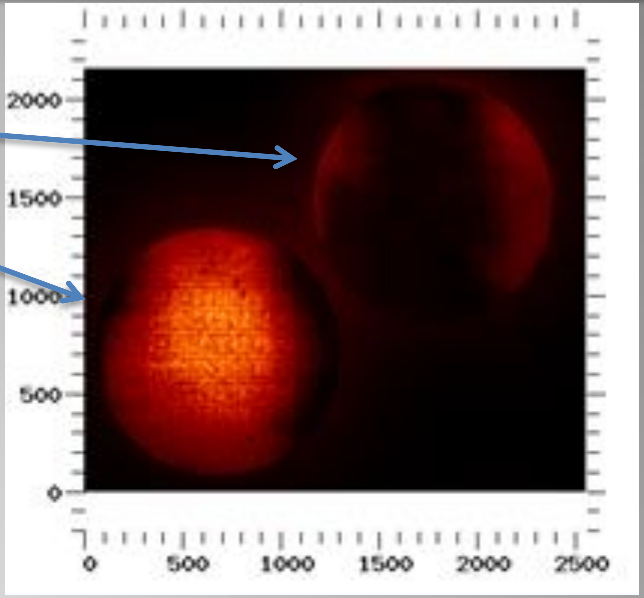
- Sources: He-Ne 632nm laser, super continuum white light
- Turbulence simulator: rotating AO-corrected phase mask-
- Wavefront sensor: Mach-Zehnder interferometer, visible-light camera
- Wavefront corrector: Spatial Light Modulator (SLM), Deformable Mirror (DM)
- Reference arm with a pinhole ~λ/D diameter

Mach-Zehnder interferometer

Model

$$I_1 = C - \mathrm{B}\sin(\varphi_1 - \varphi_2 + \delta)$$

$$I_2 = D + \mathrm{B}\sin(\varphi_1 - \varphi_2 + \delta)$$



Advantages

- For small phases variations ~ linear equation
- No noise propagation: pixel to pixel processing, on input of segmentation in the pupil
- Spatial resolution limited to the number of pixel of the camera
- The constants B, C, D can be estimated using the flux measurements of each arm of the MZ (not interfering)

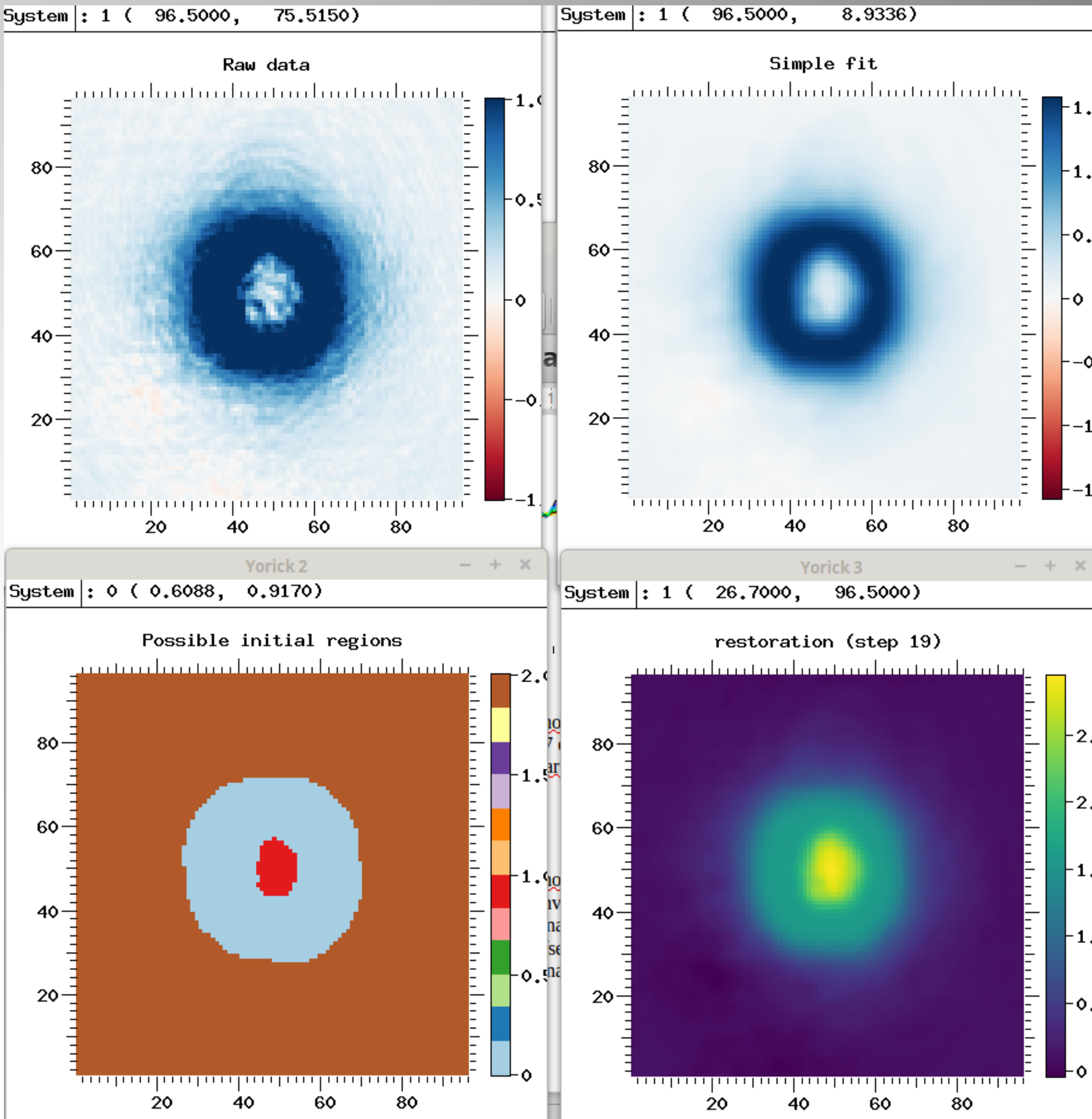
Drawbacks

- Wrapping of the phase in sinus : methods of “Desinusing”, to be used only to close the loop.
- Tip-tilt servo loop required, to minimise pinhole transmission variation

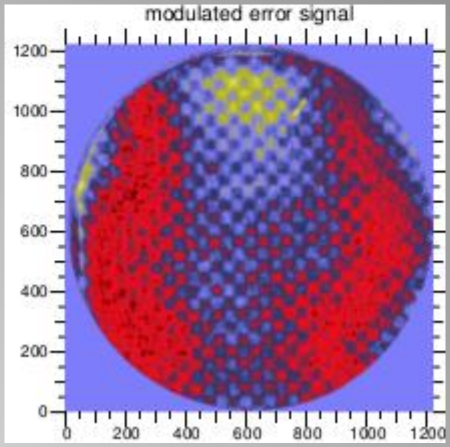
Desinusing methods

- Curvature propagation :
  - Clipping of the raw data and segmentation
  - Select a starting region whithout ambiguities
  - Fit the sinus of the phase with a curvature regularisation
  - Extrapolate

- Evaluation :
  - Sensitive to constrat variation
  - Iterative process, eventhough the number of step could be reduced
  - Still risk of failure



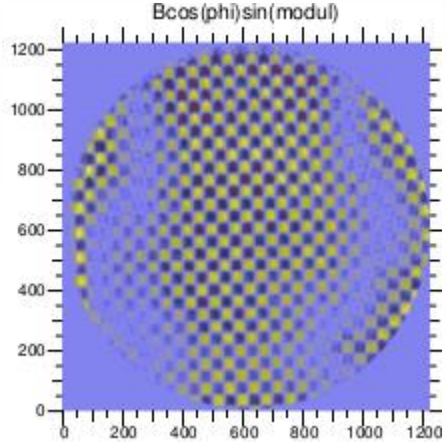
Desinusing methods

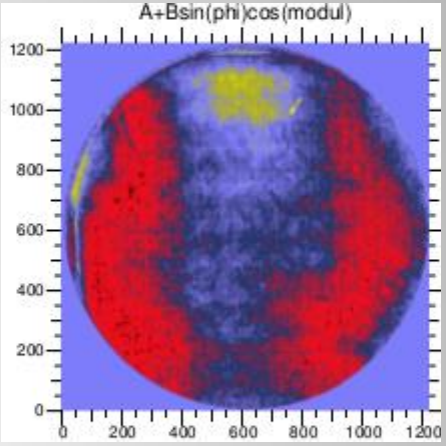


- Waffle modulation :
  - The SLM is used to send a small modulation ~0.04λ at high spatial frequencies
  - For the time being the error signal built by

E= $\frac{I_1-I_2}{I_1+I_2}$=A′ + Bsin(ϕ + $modul$) is used

  - The sum and difference of error signals are then
    - Sum/2=A+Bsin(ϕ)cos(modul)
    - Difference/2=B cos(ϕ)sin(modul)



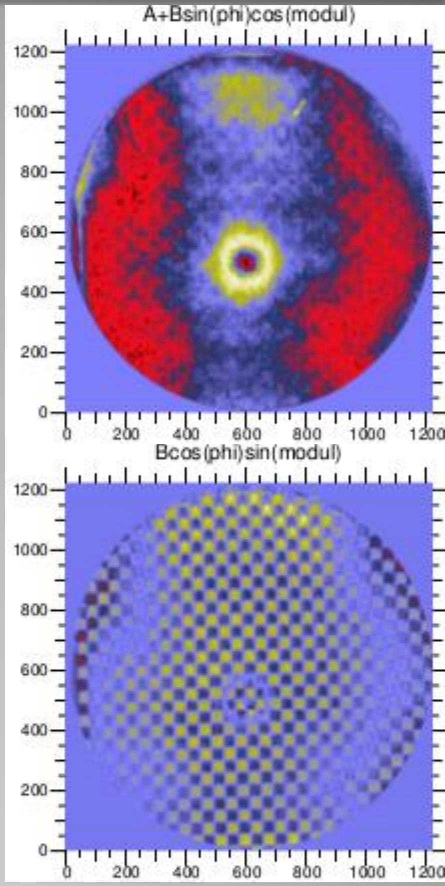


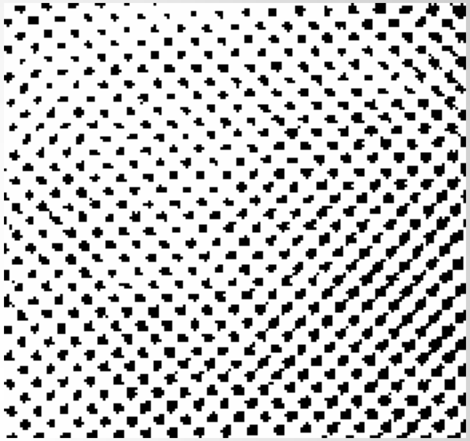
Desinusing methods

- Waffle modulation :
  - Assuming a small modulation
  - $Bcos(\emptyset)\,\sin(modul) \sim B\alpha\,\cos(\emptyset)\,sign(modul)$
  - The sign of cos(ϕ) allows to remove the ambiguity to reach ϕ [2π]
  - Classical unwrapping if necessary

OR

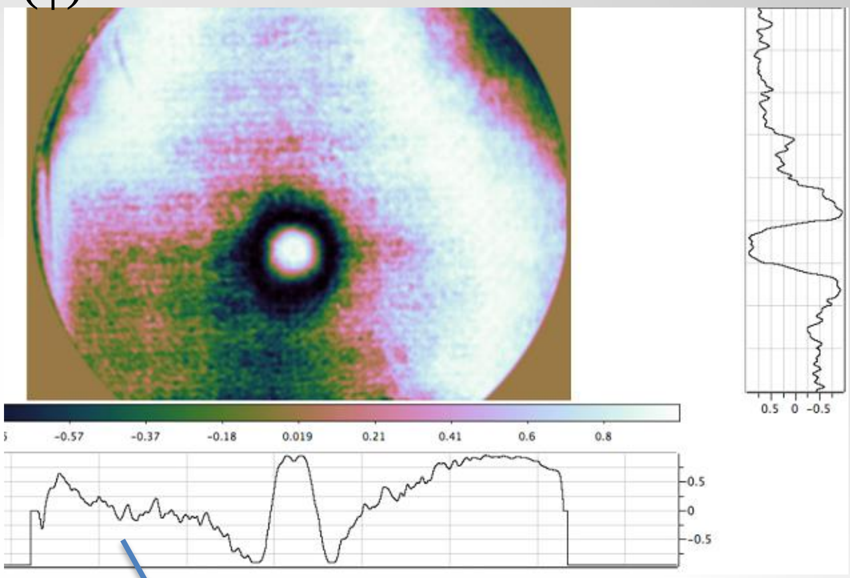
  - Calibration of the sin(modul) and cos(modul) from the data
  - Direct estimation of
    - Sin(ϕ)
    - Cos(ϕ)
  - Phase retrieved ϕ [2π]
  - Classical unwrapping if necessary



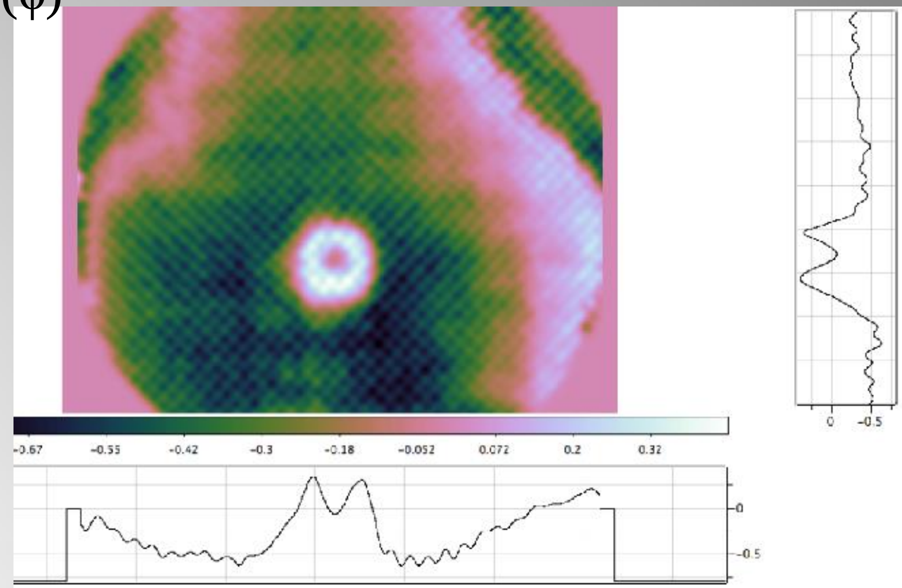


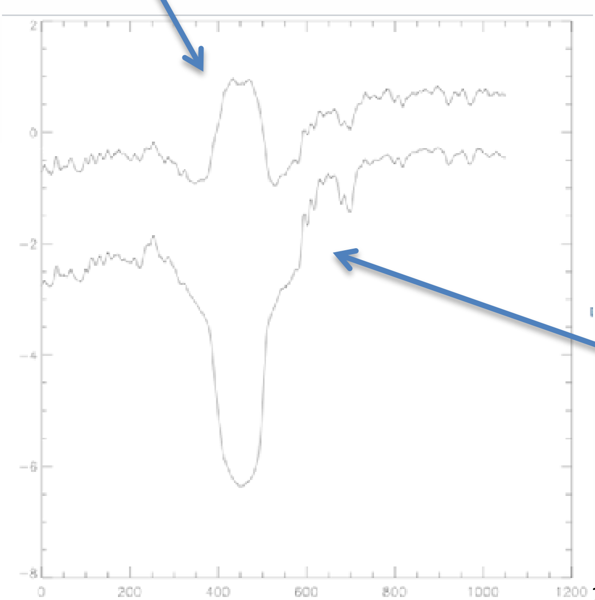
Desinusing

sin(ϕ)

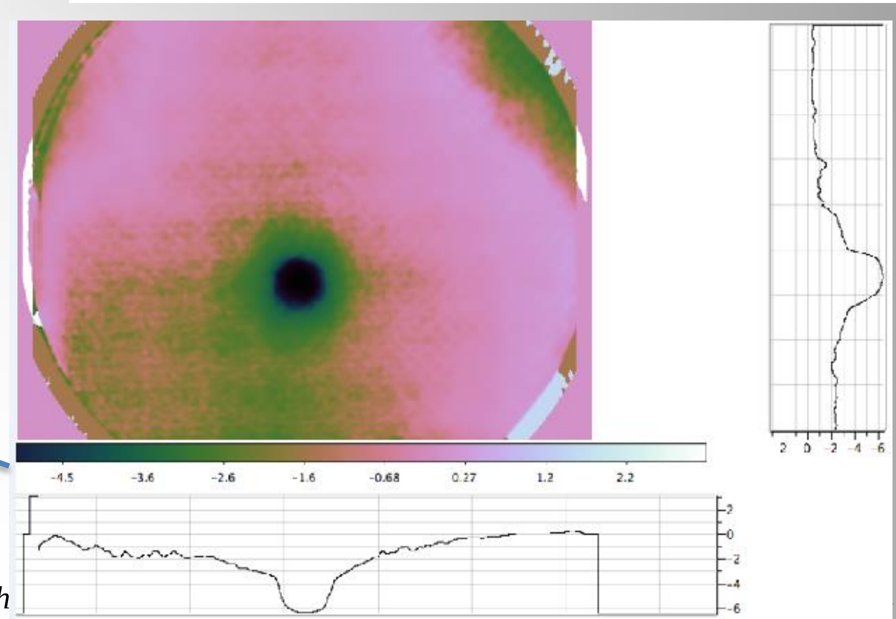


cos(ϕ)



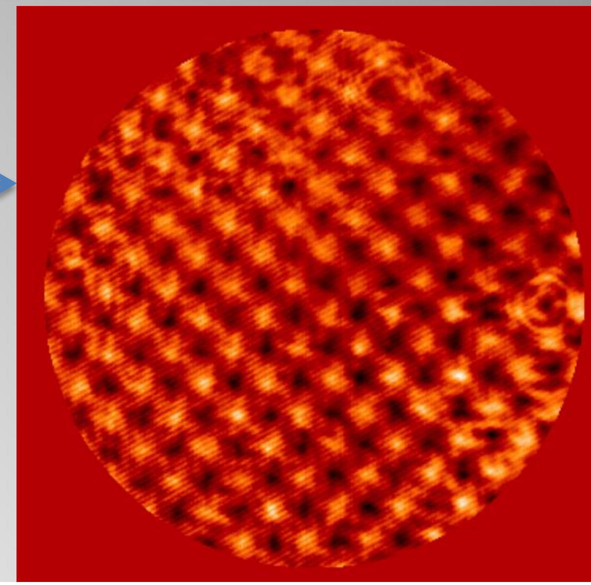


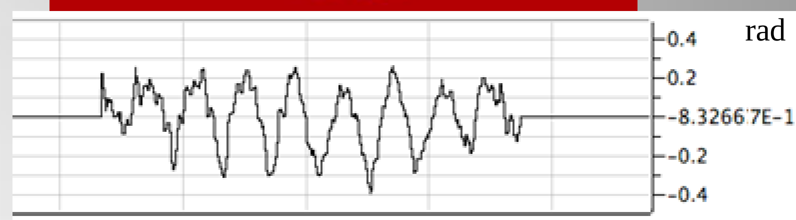
Phase ϕ



MZ sensitivity and dynamic

- Sensitivity of MZ :
  - Reconstructed modulation phase
  - 5-10nm PTV wavefront accuracy





- Dynamic increase with desinusing :
  - 1 micron PTV wavefront
- Spatial resolution suited to ELT scale ~20cm
- Set up already tested on 10-20nm spectral bandwidth sources.

Conclusion and Perspectives

Conclusion

- Desinusing techniques:
  - Curvature propagation is sensitive to contrast variation, iterative process
  - Waffle modulation : robust method.
  - Work on going: estimation of the arms flux to work directly on raw images and not on the error signal

Short and long term perspectives

- Test spectrally spread sources
- Test different control algorithms
- Implement an imaging path, to host a coronagraph and a Lyot-Stop
- Perform a Lyot-based pointing control system (LPCS)