Introduction
oo

ZELDA wavefront sensor
oooo

Closed loops with the SLM
ooooooooo

Conclusion
ooo

HARMONI at ELT: A Zernike wavefront sensor for the high-contrast module - Testbed results with realistic observation conditions.

Adrien Hours

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1 Introduction

2 ZELDA wavefront sensor to measure Quasi-Static Aberrations

3 Closed loop with the Spatial Light Modulator - Most recent results

4 Conclusion

1 Introduction

2 ZELDA wavefront sensor to measure Quasi-Static Aberrations

3 Closed loop with the Spatial Light Modulator - Most recent results

4 Conclusion

- One of the top level requirements of HARMONI: perform direct imaging and spectral analysis of exoplanets with a flux ratio of 10^{-6} at 50mas.
  - to understand their formation process;
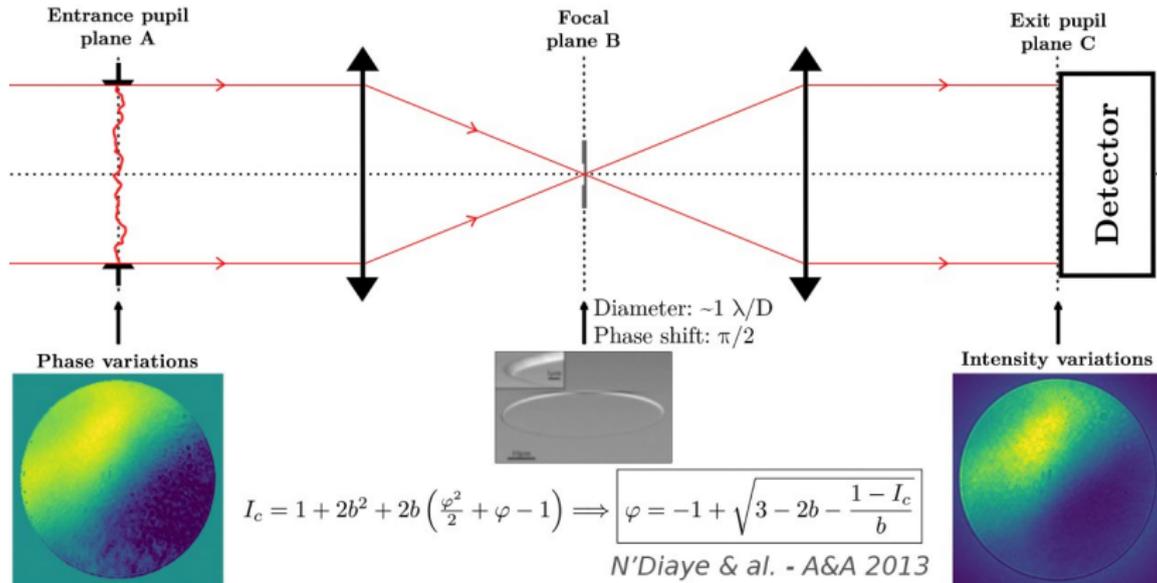 - to discover new exoplanets.

Context

- One of the top level requirements of HARMONI: perform direct imaging and spectral analysis of exoplanets with a flux ratio of 10^{-6} at 50mas.
    - to understand their formation process;
    - to discover new exoplanets.

- To reach such a contrast, we have to measure and calibrate NCPA.

- Intrinsic issues:
    - Turbulence
    - Photon noise
    - NCPA
      (Non Common Path Aberrations)

- Solutions:
    - SCAO
    - Coronagraphy*
    - ZELDA wavefront sensor
    - Post-processing

* *A bench is developped at IPAG to experiment the coronagraphy aspect*

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  - Coronagraphy* ←-----
  - ZELDA ←----- *problems?*
    wavefront sensor ←-----
  - Post-processing ←----- *asset?*

- HARMONI's specific features:
  - ELT pupil
  - no ADC
  - no XAO
  - High Spectral Resolution

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Introduction
○●
ZELDA wavefront sensor
○○○○
Closed loops with the SLM
○○○○○○○○○
Conclusion
○○○

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1 Introduction

2 ZELDA wavefront sensor to measure Quasi-Static Aberrations

**3** Closed loop with the Spatial Light Modulator - Most recent
results

4 Conclusion

Introduction
oo

ZELDA wavefront sensor
o●oo

Closed loops with the SLM
oooooooooo

Conclusion
ooo

ZELDA WFS principle

$$I_c = 1 + 2b^2 + 2b\left(\frac{\varphi^2}{2} + \varphi - 1\right) \implies \boxed{\varphi = -1 + \sqrt{3 - 2b - \frac{1 - I_c}{b}}}$$

N'Diaye & al. - A&A 2013

- Measure the phase directly ⇒ Sensitive to Island and low-wind effects

Typical wavefront
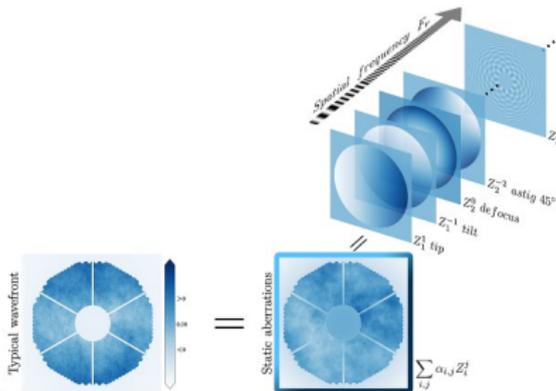
- ZELDA signal is affected by:
  - **quasi-static aberrations (QSA)**;

Introduction
○○

ZELDA wavefront sensor
○○○●

Closed loops with the SLM
○○○○○○○○○

Conclusion
○○○

Typical wavefront

- ZELDA signal is affected by:
  - **quasi-static aberrations (QSA)**;
  - residual refraction which induces a chromatic tilt;

Introduction
○○

ZELDA wavefront sensor
○○○●

Closed loops with the SLM
○○○○○○○○○

Conclusion
○○○
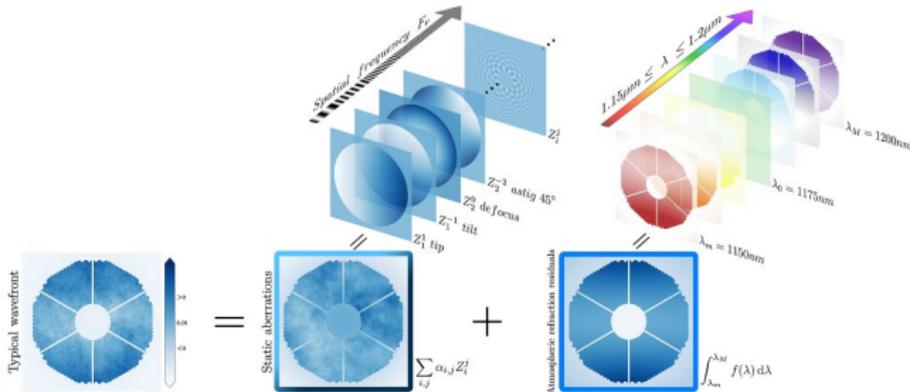
Typical wavefront

- ZELDA signal is affected by:
  - **quasi-static aberrations (QSA)**;
  - residual refraction which induces a chromatic tilt;
  - turbulence residuals which induce HF aberrations.
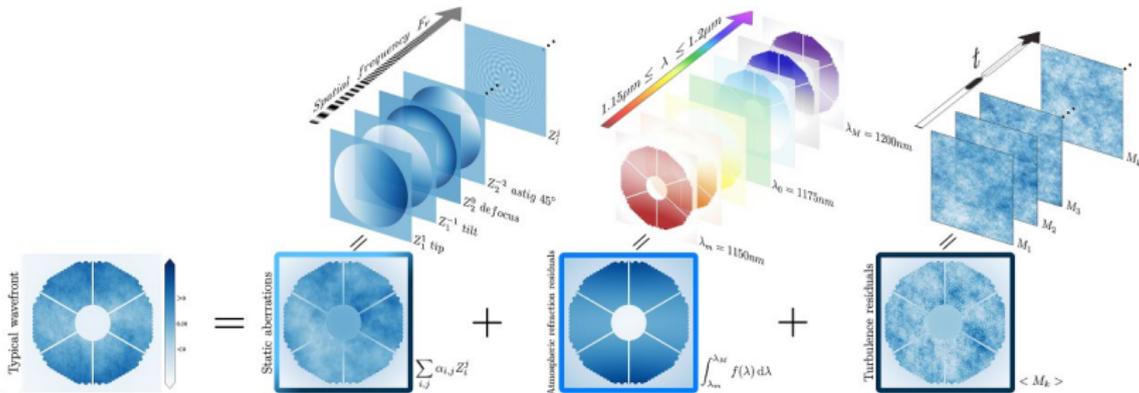
ZELDA experimental bench set up at IPAG

The ZELDA WFS works at $\lambda = 1.15\text{-}1.2\mu$m. Science above 1.25μm.

- XYZ motorized stages $\rightarrow$ minimise tip, tilt and defocus (closed loop);
- ADC $\rightarrow$ mimic the atmospheric refraction residuals (ZD$= 53°$);
- SLM $\rightarrow$ mimic both typical turbulence residuals and static aberrations.
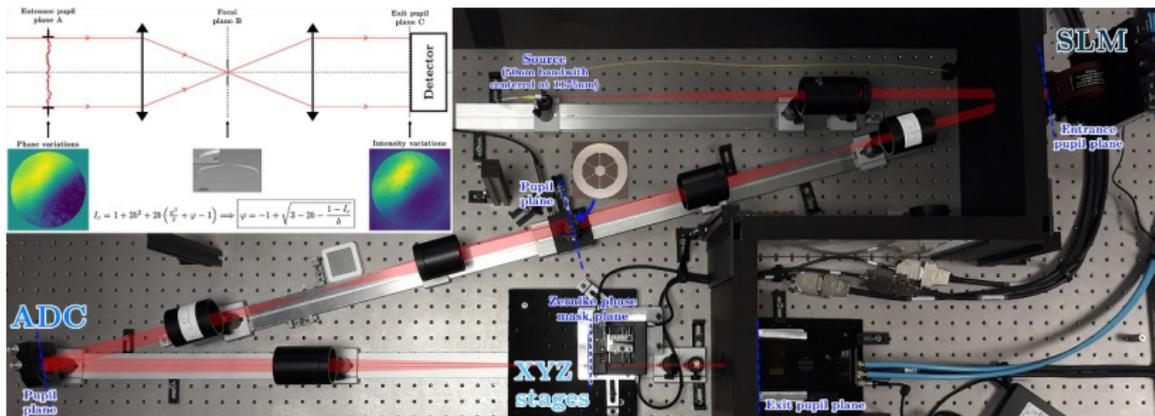
ZELDA experimental bench set up at IPAG
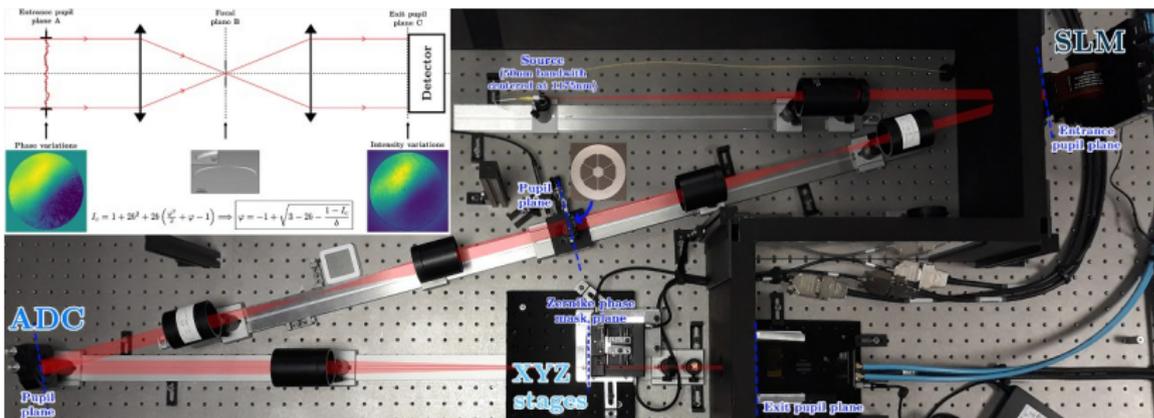
- ZELDA range: 60nm rms
- Goal: corrected WFE $\leq$ 5nm rms (in 0-40 λ/D spatial frequencies range)
- Frequency: a WFE measurement every 10-15s

1 Introduction

2 ZELDA wavefront sensor to measure Quasi-Static Aberrations

3 Closed loop with the Spatial Light Modulator - Most recent results

4 Conclusion

Ideal case - Neither dispersion nor AO residuals – Simulations
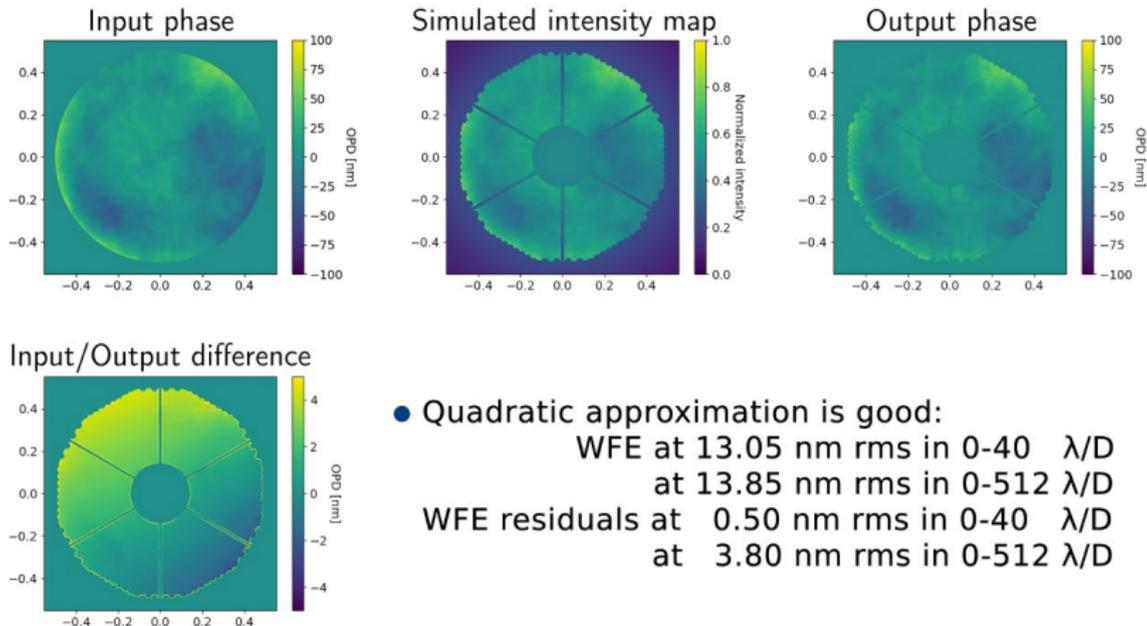
- Quadratic approximation is good:
  WFE at 13.05 nm rms in 0-40   λ/D
  at 13.85 nm rms in 0-512 λ/D
  WFE residuals at   0.50 nm rms in 0-40   λ/D
  at   3.80 nm rms in 0-512 λ/D

Ideal case - Neither dispersion nor AO residuals – Experimentation

Experimental intensity map
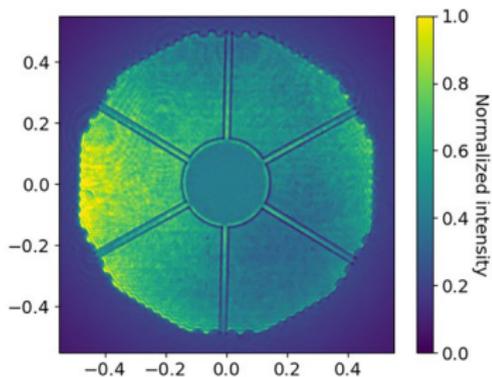
Experimental estimated phase
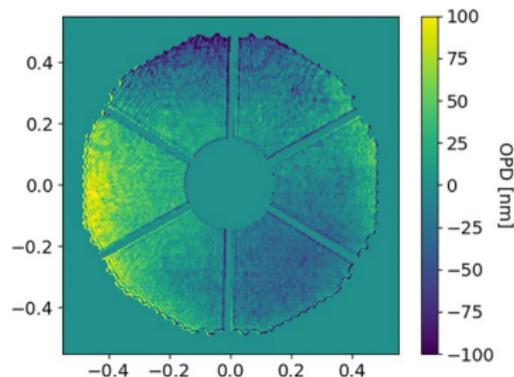
Ideal case - Neither dispersion nor AO residuals – Closed loop results
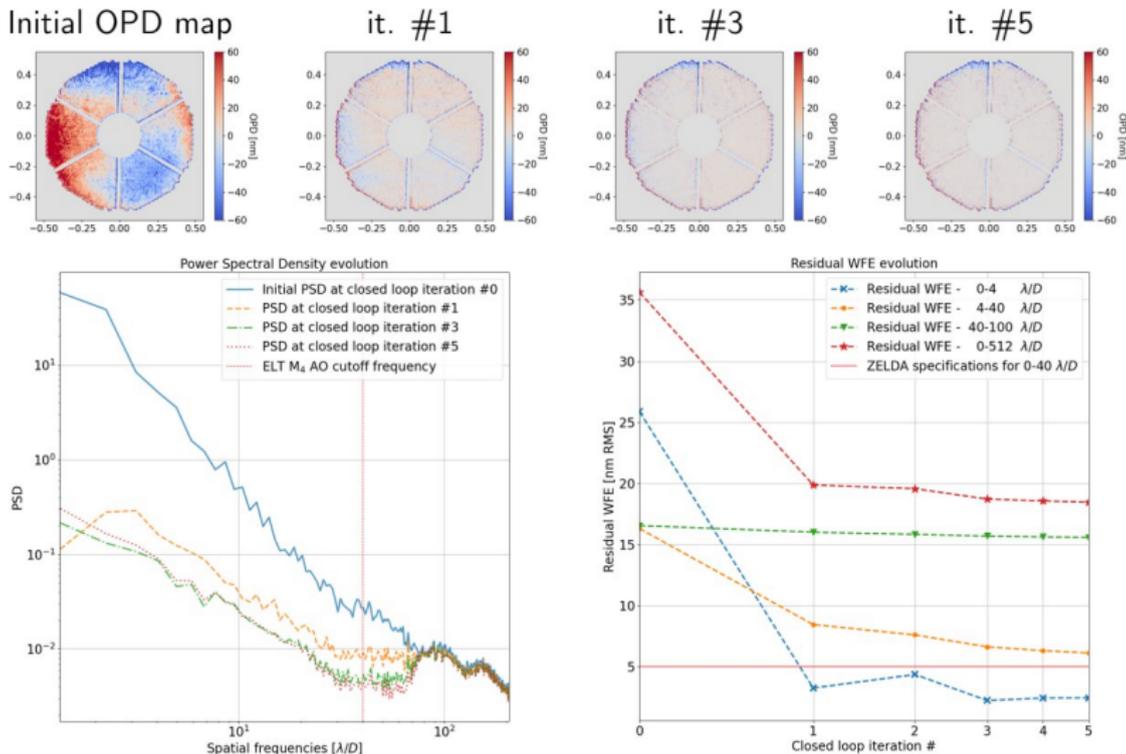
- Good correction, stable loop, fast convergence.

Introduction
OO

ZELDA wavefront sensor
OOOO

Closed loops with the SLM
OOOO●OOOO

Conclusion
OOO

Dispersion residuals – One prism to disperse them all

Simulated PSF w/o dispersion
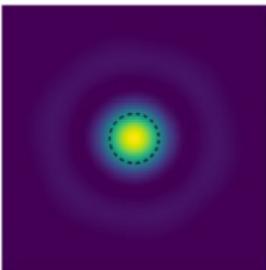
Simulated PSF with dispersion BW 50nm, ZD 50°

Dispersion signal

Zenith Distance [°]
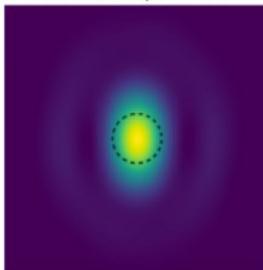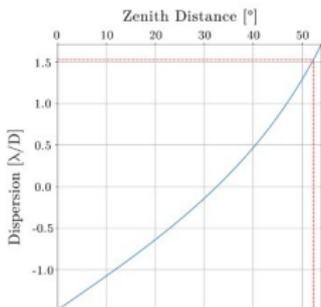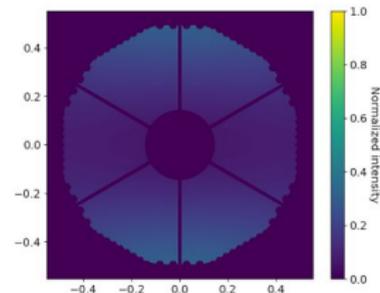
Experimental PSF with dispersion BW 50nm

1 pixel = 15x15μm
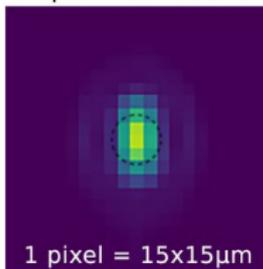
- Introduced dispersion: 1.53 λ/D ⇔ ZD of 53° (beyond HCM limits)

Dispersion residuals – Simulations

Uncalibrated intensity map
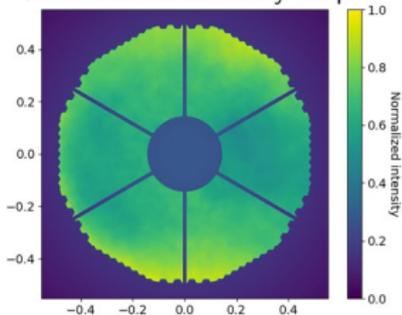
Calibrated intensity map
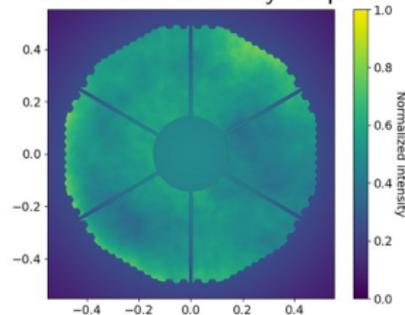
Uncalibrated OPD map
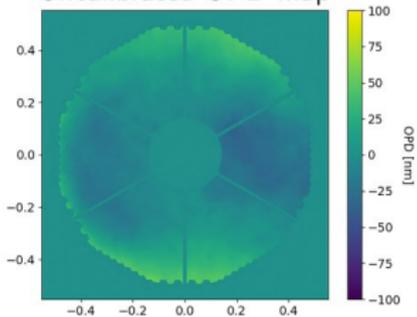
Calibrated OPD map
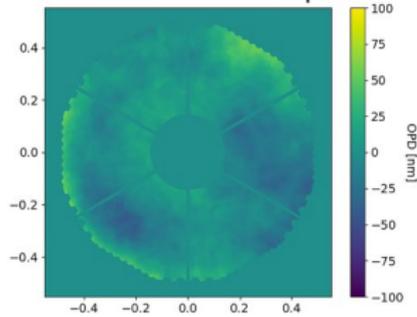
Dispersion residuals – Simulations

Real OPD map
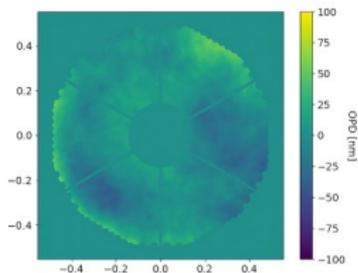
Real-Uncalibrated
difference

Real-Calibrated
difference

WFE:
13.05 nm rms in 0-40 λ/D
13.85 nm rms in 0-512 λ/D
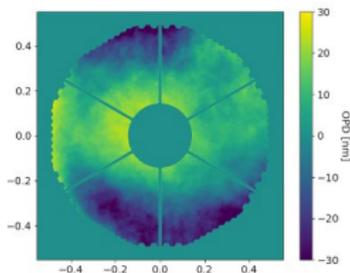
WFE residuals:
11.45 nm rms in 0-40 λ/D
11.87 nm rms in 0-512 λ/D
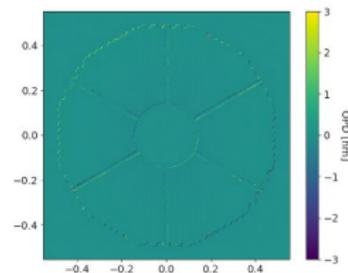
WFE residuals:
0.09 nm rms in 0-40 λ/D
0.76 nm rms in 0-512 λ/D

- The atmospheric refraction residuals must be calibrated!

Dispersion residuals – Experimentation

Uncalibrated experimental intensity map
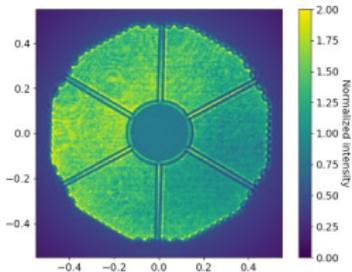
Computed dispersion signal with experimental pupil
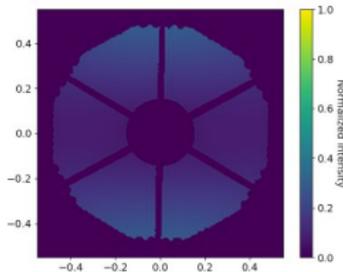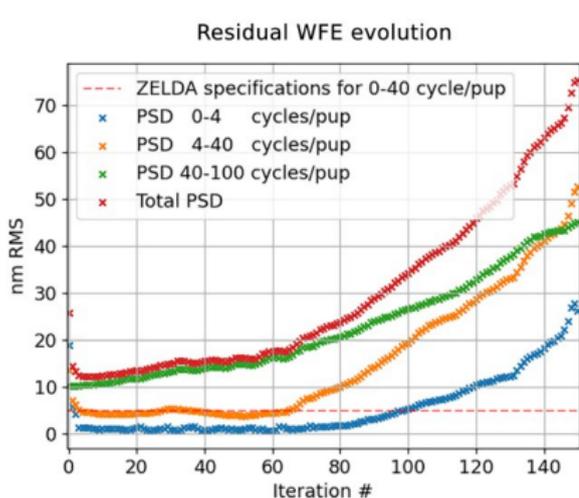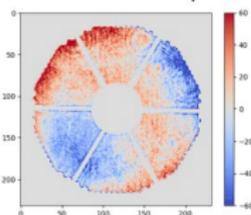
Calibrated experimental intensity map

Introduction
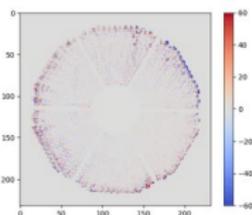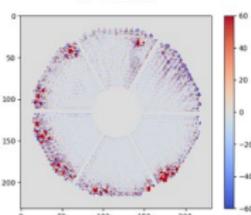ZELDA wavefront sensor
Closed loops with the SLM
Conclusion
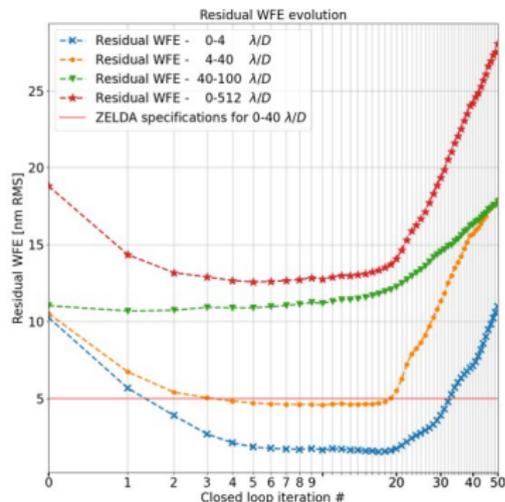
Dispersion residuals – Closed loop results
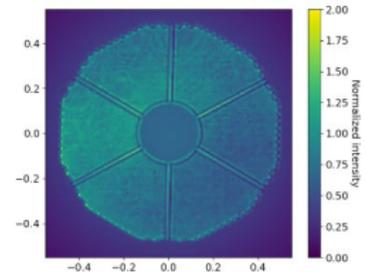
Initial OPD map   it. #3   it. #25   it. #50
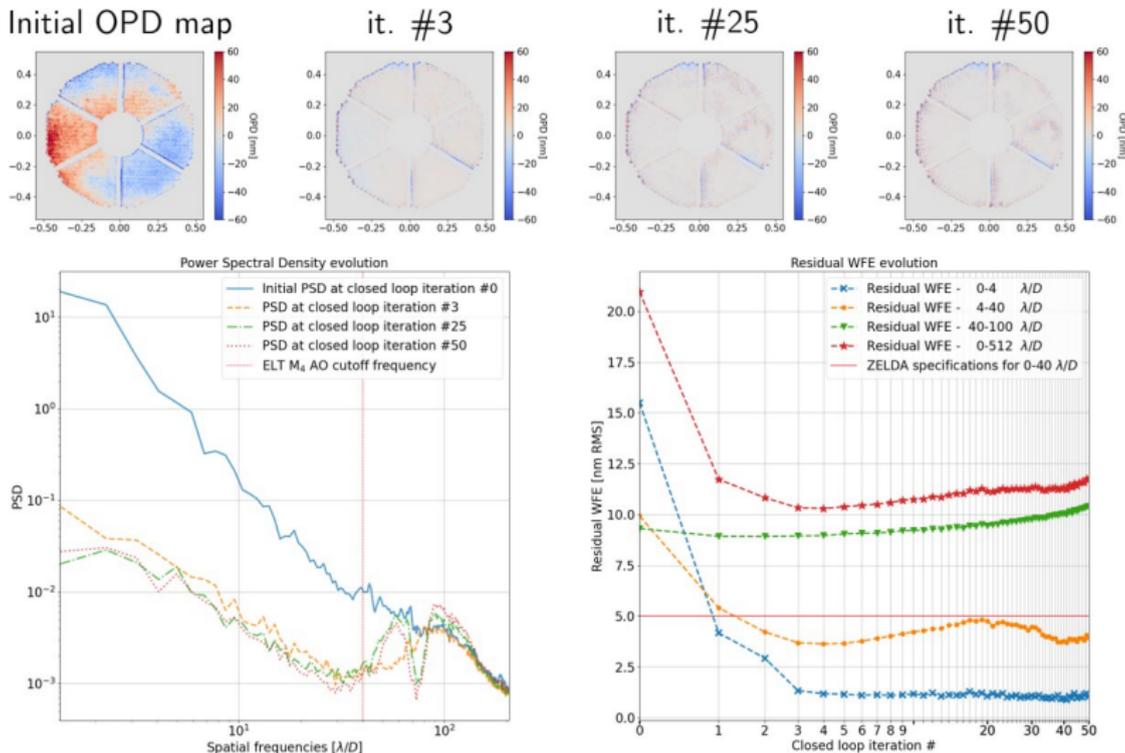
- Taking chromaticity into account → stable loop (TBC)
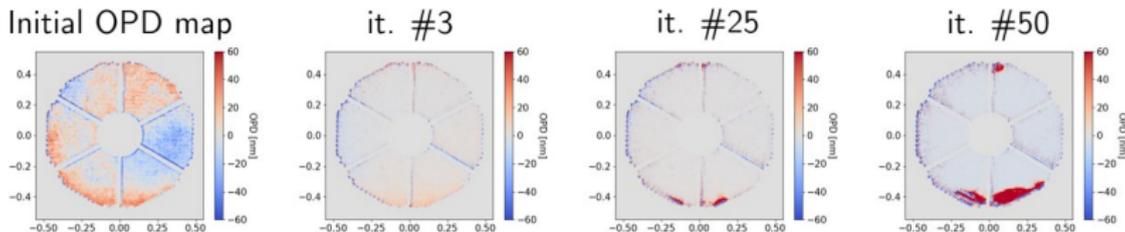
Introduction
OO

ZELDA wavefront sensor
OOOO

Closed loops with the SLM
OOOOOOOO●O

Conclusion
OOO

Dispersion residuals – Closed loop results

Introduction
ZELDA wavefront sensor
Closed loops with the SLM
Conclusion

Dispersion residuals – Closed loop results

Initial OPD map   it. #3   it. #25   it. #50
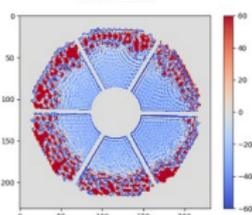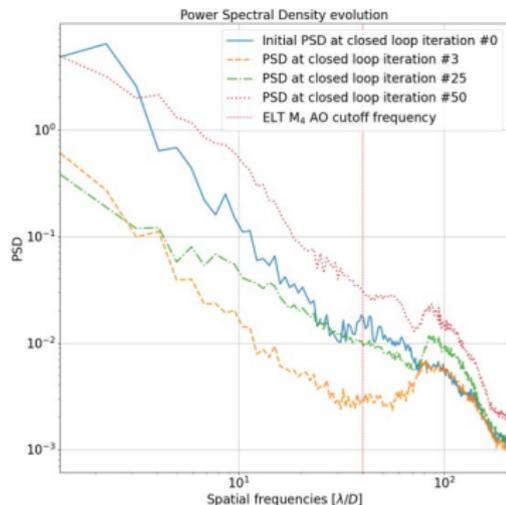
- No account taken of chromaticity → unstable loop.

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Wavefront Sensing in the VLT/ELT era VII — Porto 2022
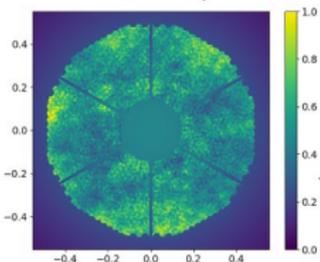16 / 20

AO residuals – Simulations VS experimentation
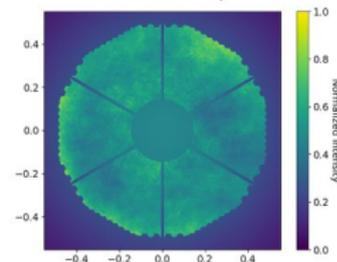
Intensity map with 1 map of the
datacube on top of input phase
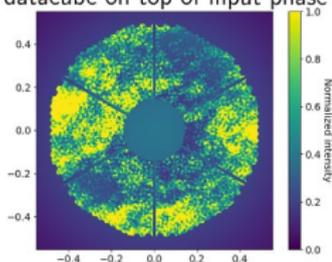
With 10 maps

With 100 maps

- 100 independant OPD maps datacube to mimic AO residuals.

QSA Intensity map

| Spatial frequencies region		0-4 λ/D	4-40 λ/D	40-100 λ/D	"all" (0-512 λ/D)
$\overline{\varphi_{out}}$	[nm rms]	10.80	7.33	2.23	13.85
$\Delta\overline{\varphi_{out\text{-}1}}$	[nm rms]	33.97	31.42	23.79	52.51
$\Delta\overline{\varphi_{out\text{-}10}}$	[nm rms]	10.09	12.27	9.50	18.71
$\Delta\overline{\varphi_{out\text{-}100}}$	[nm rms]	3.75	3.98	3.01	6.32

- Averaging over a sufficient number of OPD map ($\equiv$ Temporal averaging over a sufficiently long time)→accessible QSA signal.
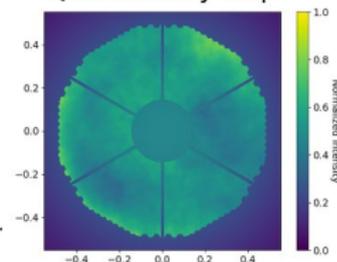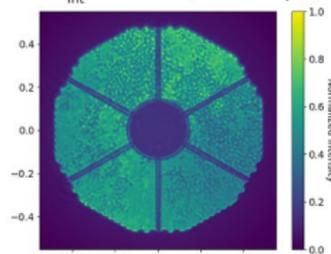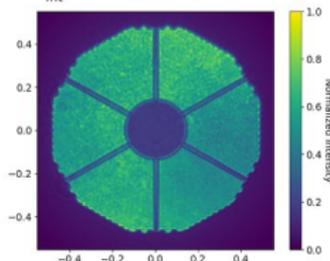
AO residuals – Simulations VS experimentation

Experimental intensity map
with t_{int} = 6.67ms (≡1 map)
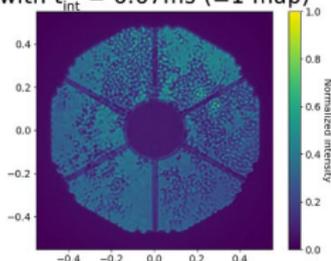
With t_{int} = 67ms (≡10 maps)

With t_{int} = 667ms (≡ 100 maps)

- Datacube sent to the SLM at a frequency of ~150 Hz

Experimental QSA
Intensity map (flat SLM)
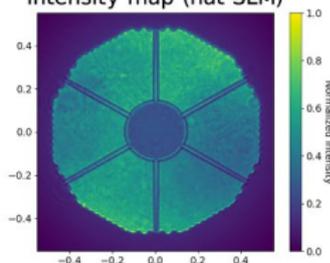
- Averaging over a sufficient number of OPD map (≡ Temporal averaging over a sufficiently long time)→accessible QSA signal.
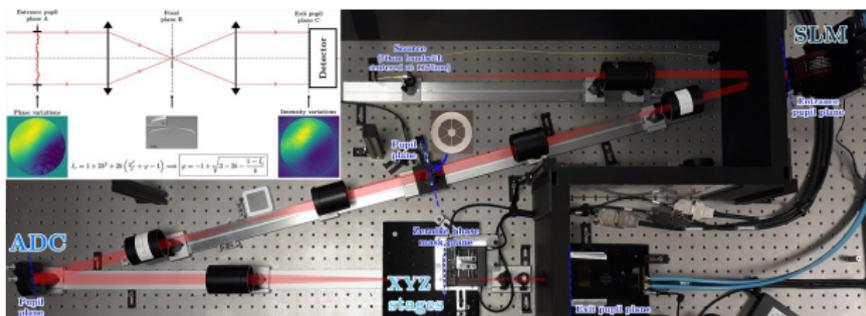
1 Introduction

2 ZELDA wavefront sensor to measure Quasi-Static Aberrations

3 Closed loop with the Spatial Light Modulator - Most recent results

4 Conclusion

Where are we and what's next?

- Working sub-nanometer sensitivity sensor.
- Validation of the ZELDA with dispersion residuals.
  ↪ (0-40 λ/D: 4.19 < 5 nm rms)

- Test the stability (> 1000 iterations).
- Close a loop despite both dispersion and AO residuals.
- Work with typical magnitudes expected with HARMONI.
- Close a loop using an interaction matrix.
- Defend my thesis and find a postdoc!

A bench to measure the accuracy of the ZELDA WFS by (1) reproducing realistic observation conditions and (2) closing a loop up to 40 λ/D.

Thank you for your attention!