Characterisation of a Pyramid WFS:
an experimental study

Charlotte Bond,
C. M. Correia, J.-F. Sauvage, K. El Hadi, Y. Abautret, B. Neichel, T. Fusco, J.-P. Véran, G. Herriot, D. Andersen. M. Lamb, M. Van Kooten.

30th June 2017, AO4ELT V, Tenerife.

Contents

- Motivation and introduction to the bench.
- Calibration using different modal bases.
- Investigations of non-linear behaviour and impact of ‘optical gain’.
- Closed loop performance and agreement with models.

Preparation for future AO systems

Many future instruments will include a Pyramid WFS

- KPIC (IR Pyramid on Keck)
- Sphere upgrade
- Subaru
- E-ELT, TMT, GMT

Challenges

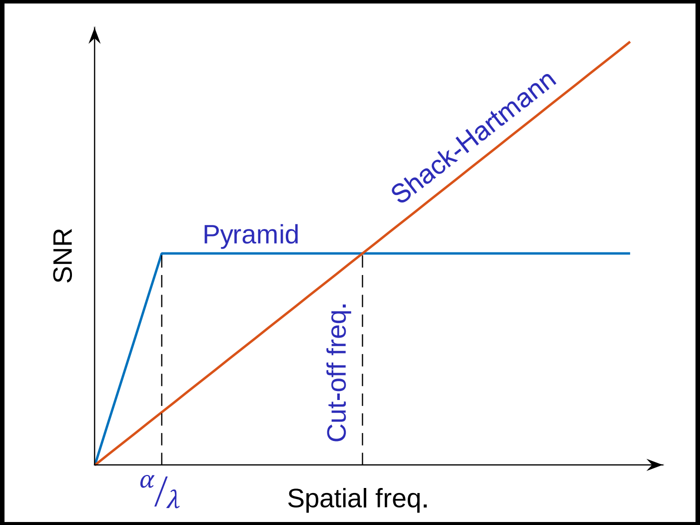
- Exploit full potential of PWFS
- Calibration
- NCPA compensation
- Non-linear behaviour

Aims

- Test non-linear behaviour
- Optimisation (gain tracking)
- Characterisation of performance.

Advantages over Shack-Hartmann

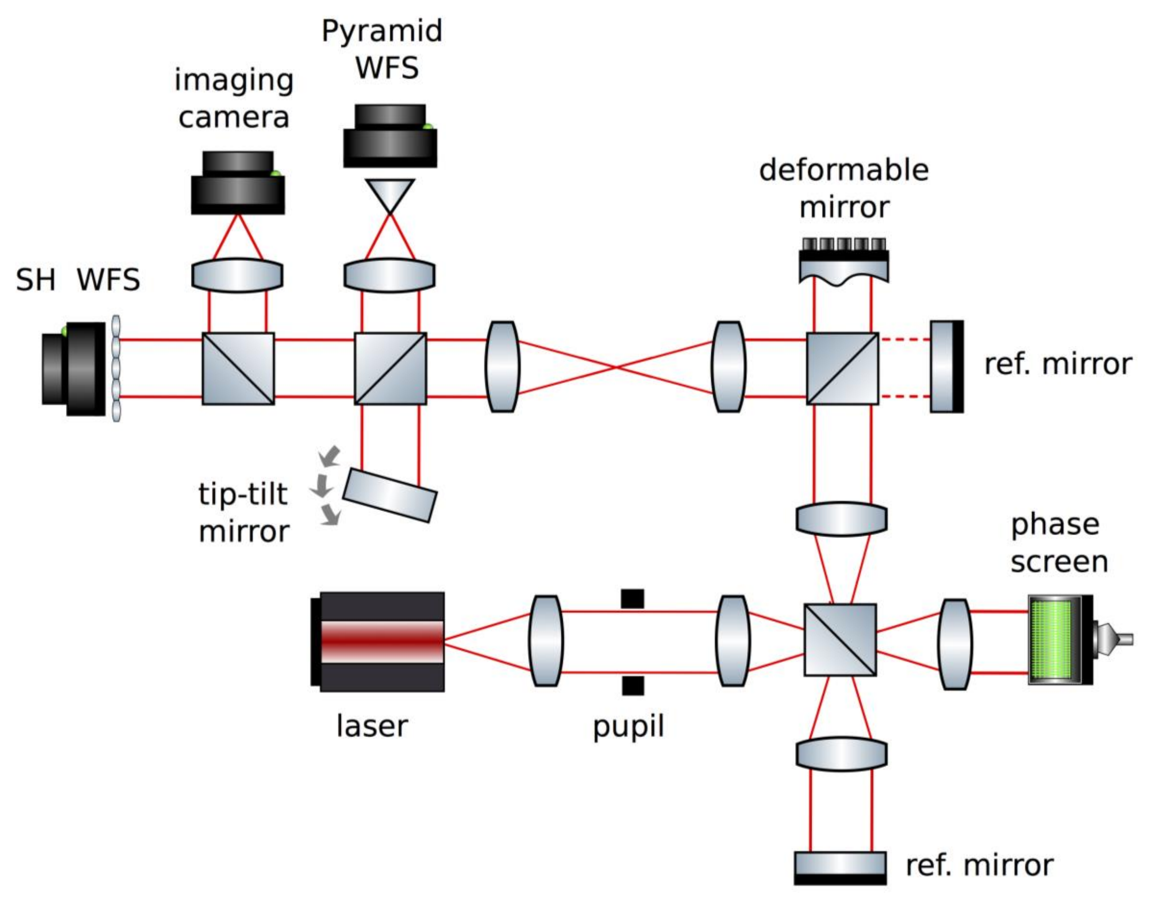
- Potential for increased sensitivity within the correction band.
- Less susceptible to aliasing.
- Flexibility: modulation allows for adjustment of linear range for different conditions.



[1] C. Verinaud 2004.

LAM bench: optical layout

- Complete AO loop (WFS, DM, turbulence, etc.).
- Bench operated using OOMAO simulation code.
- Deformable-mirror: **9x9 Alpao**.
- WFS: **62x62 pixels** (over-sampled).



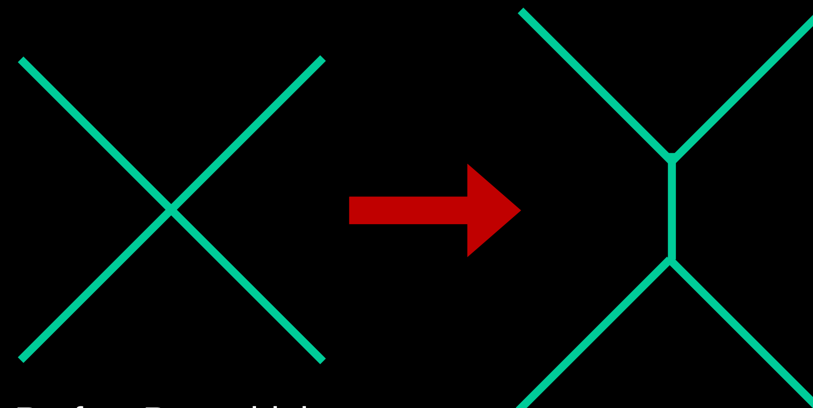
Goals

- Gain experience running AO system with Pyramid WFS.
- Investigate non-linear behaviour and measure optical gain.
- Tolerance for NCPA correction.
- Development of error budget: characterisation under different operating conditions.

Calibration and initial tests

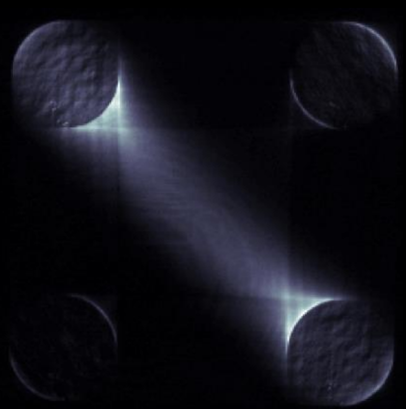
First Pyramid signals

- Initial images of Pyramid pupil demonstrate ‘roof-top’ effect at low modulation.
- Preferential distribution of light along one diagonal.

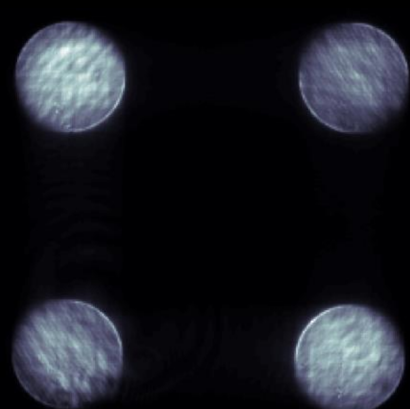


Perfect Pyramid tip

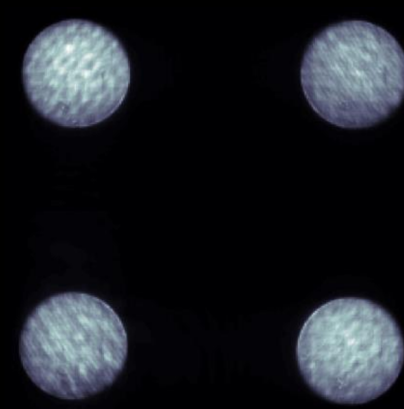
Pyramid tip with ‘roof-top’



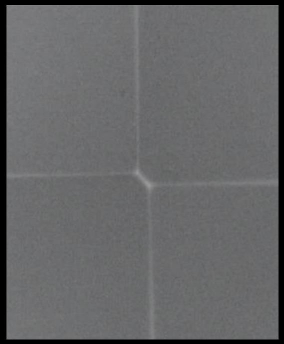
No modulation



Modulation 2λ/D



Modulation 5λ/D

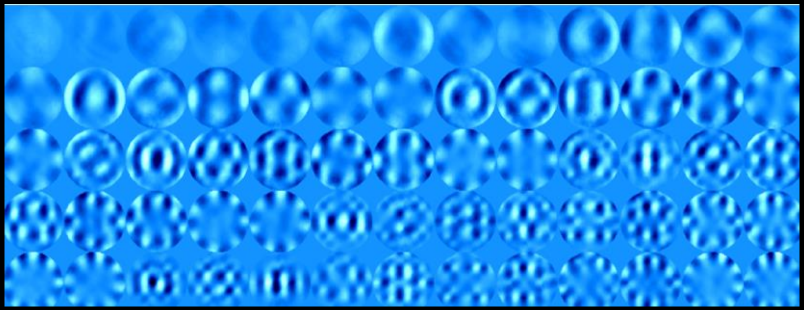


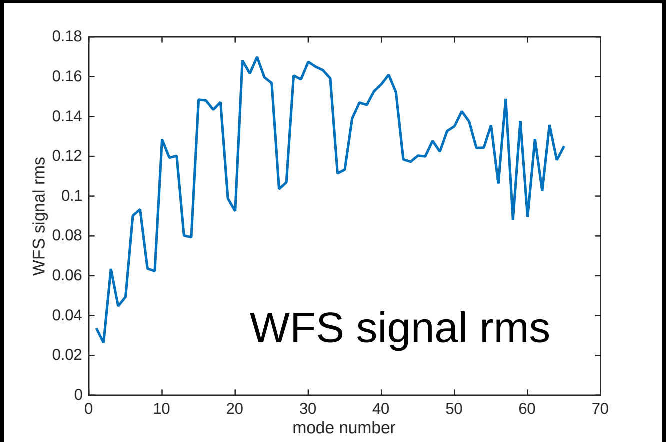
Roof-top measurement

System calibration:
measuring the interaction matrix

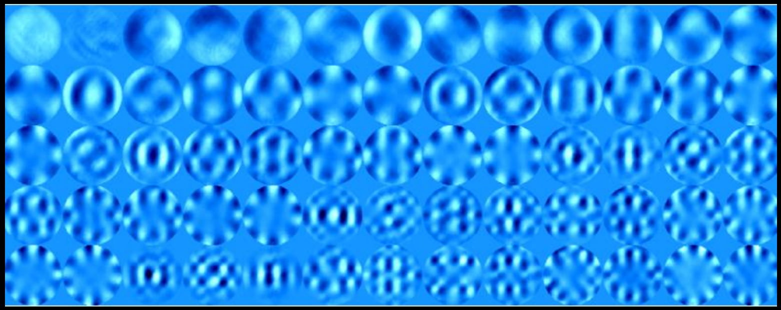
- Interaction matrix taken with 65 Zernike modes (modulation 3 λ/D shown).

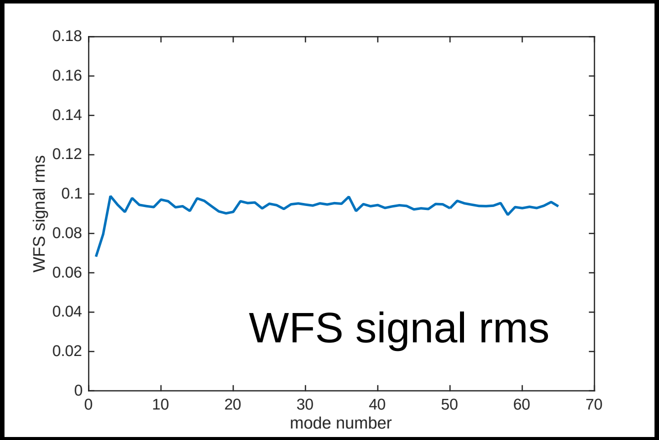
10 nm rms for each applied mode – Pyramid sensitivty varies by mode





Modes weighted to maximise the SNR for each mode

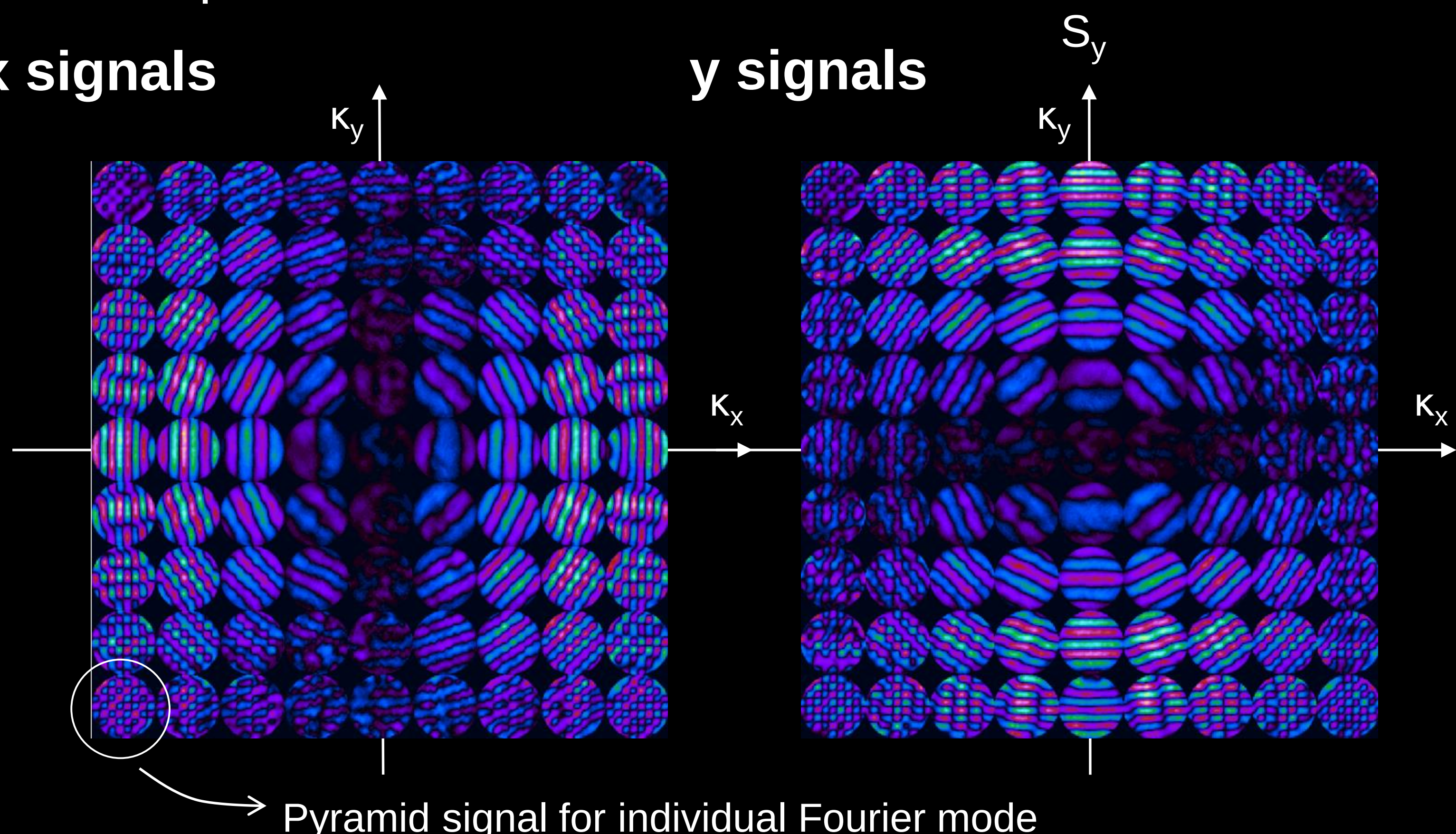




Calibration with Fourier modes

- Development of spatial frequency domain models for Fourier reconstruction and computation of error budgets (HARMONI, Keck IR Pyramid etc.).*
- Corroboration with experimental results.

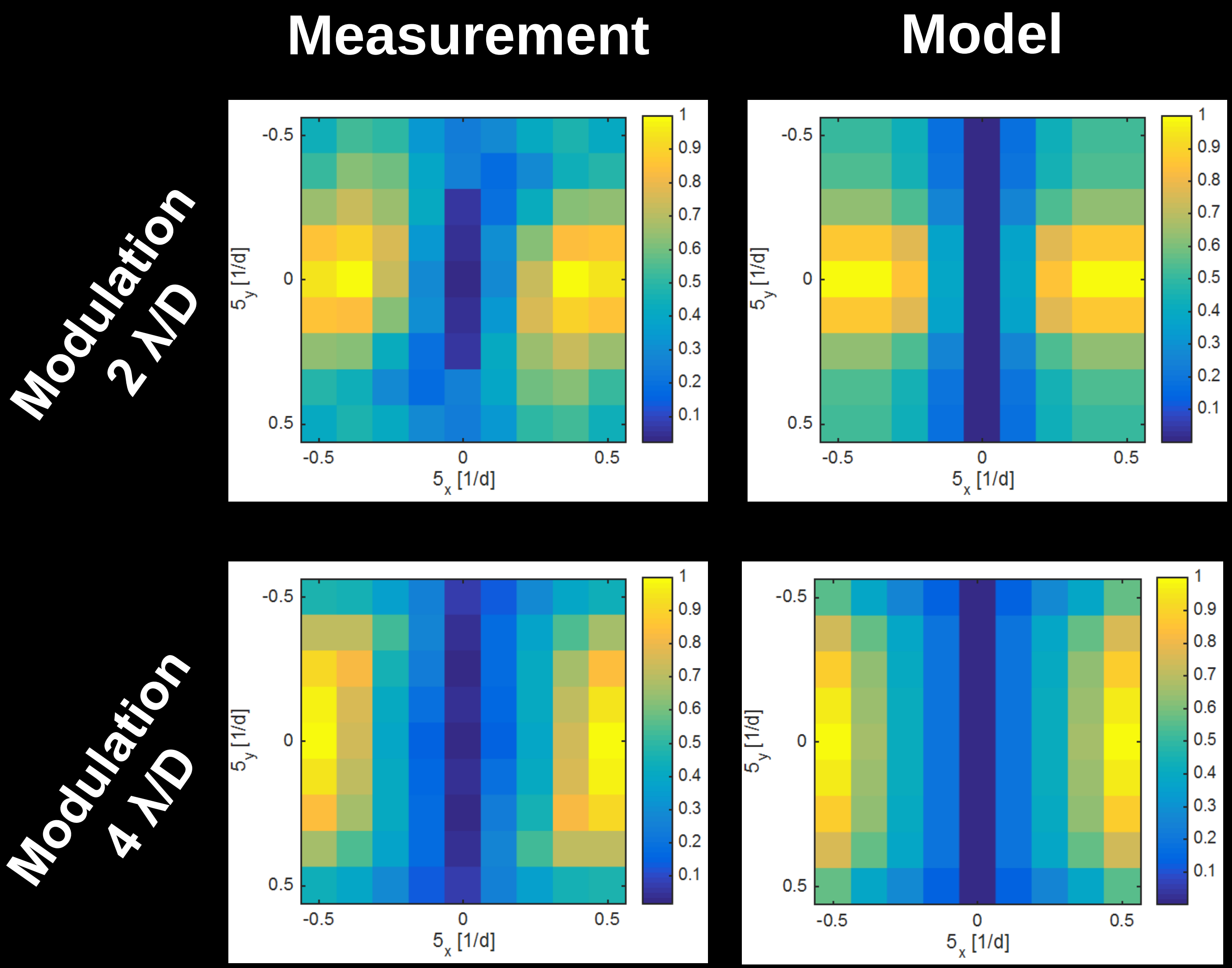
Pyramid response to Fourier modes: **modulation of 3λ/D.**



* Model detailed in poster P3033.

Calibration: comparison with models

- Pyramid response in the Fourier domain (x signals).*
- Slope-like response at low spatial frequency.
- Similar features in model and measurement.

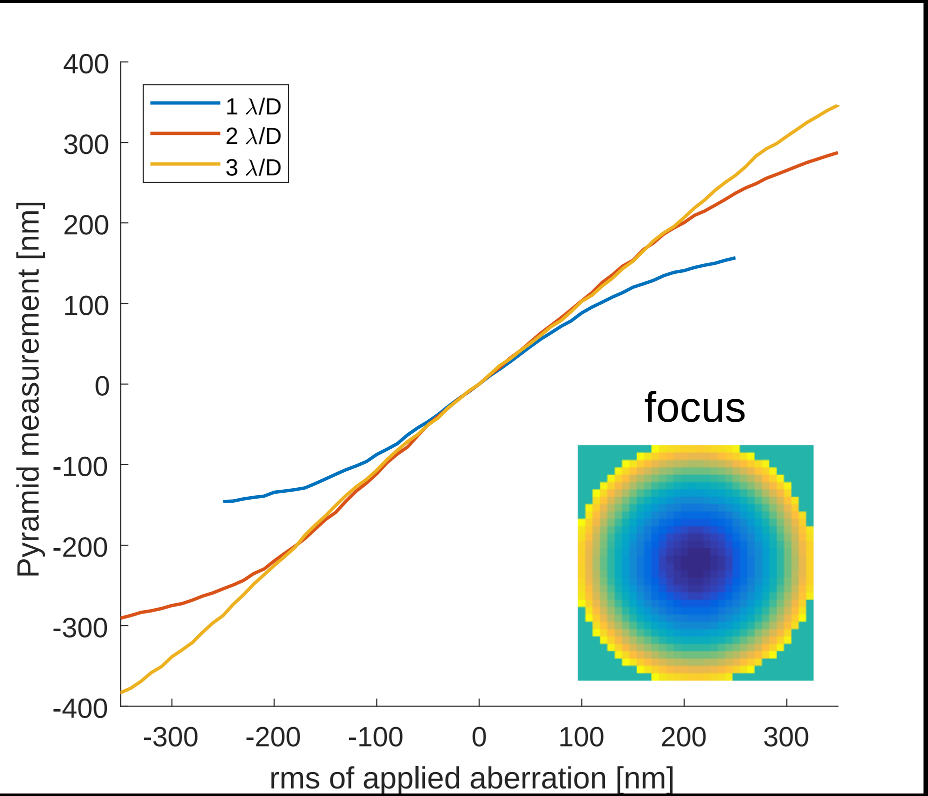


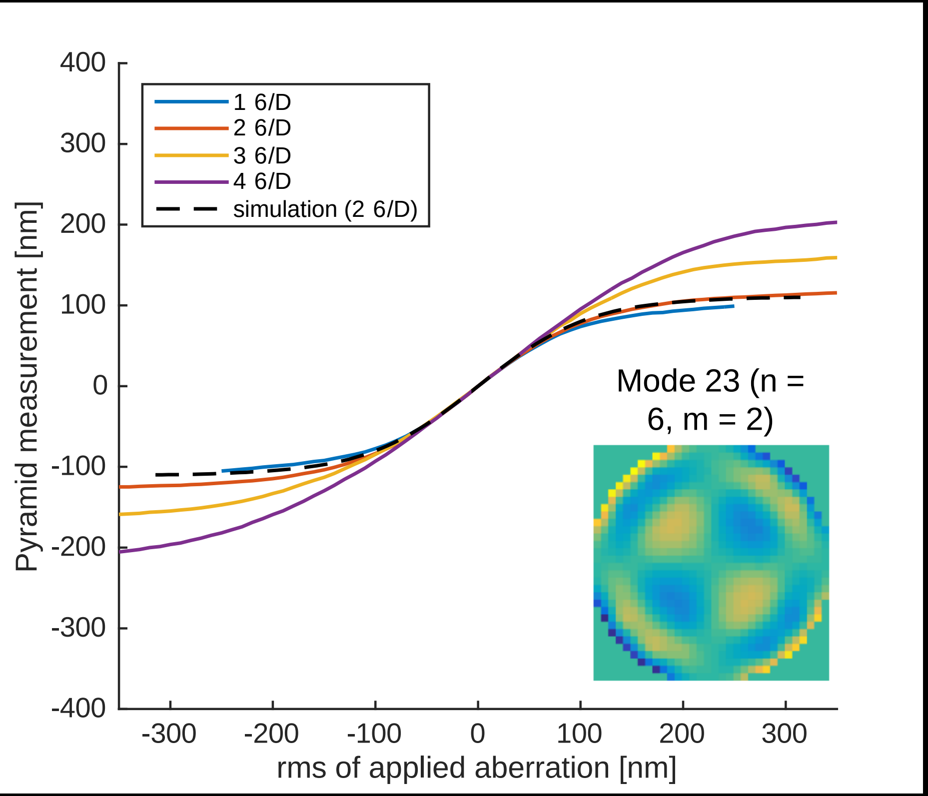
* See poster P3033.

Linearity and working off-null

Linear range

- How does the Pyramid behave in the non-linear regime (optical gain < 1)?
- The linear range varies depending on the mode and increases with modulation.





Laboratory measurement of linearity for different modes over a range of modulation.

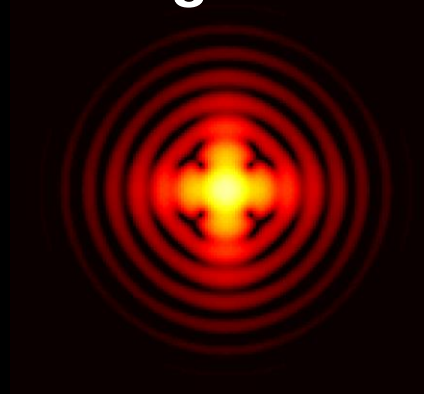
Optical gain and the Pyramid WFS

Diffraction limited, working around 0

optical gain = 1

- Diffraction limited spot on the Pyramid.
- Calibration state.

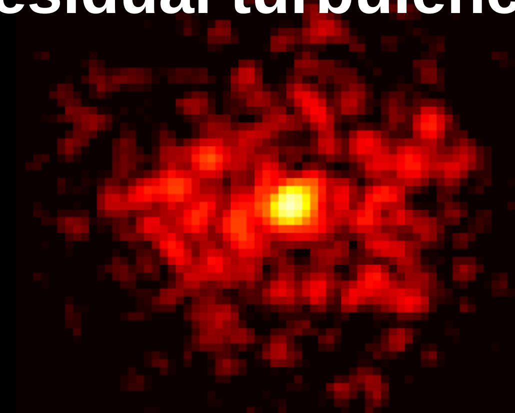
Offset operation, working off null



optical gain < 1

- Compensation of NCPA requires offset signals.
- Large NCPA → non-linear regime.

On sky operation, residual turbulence

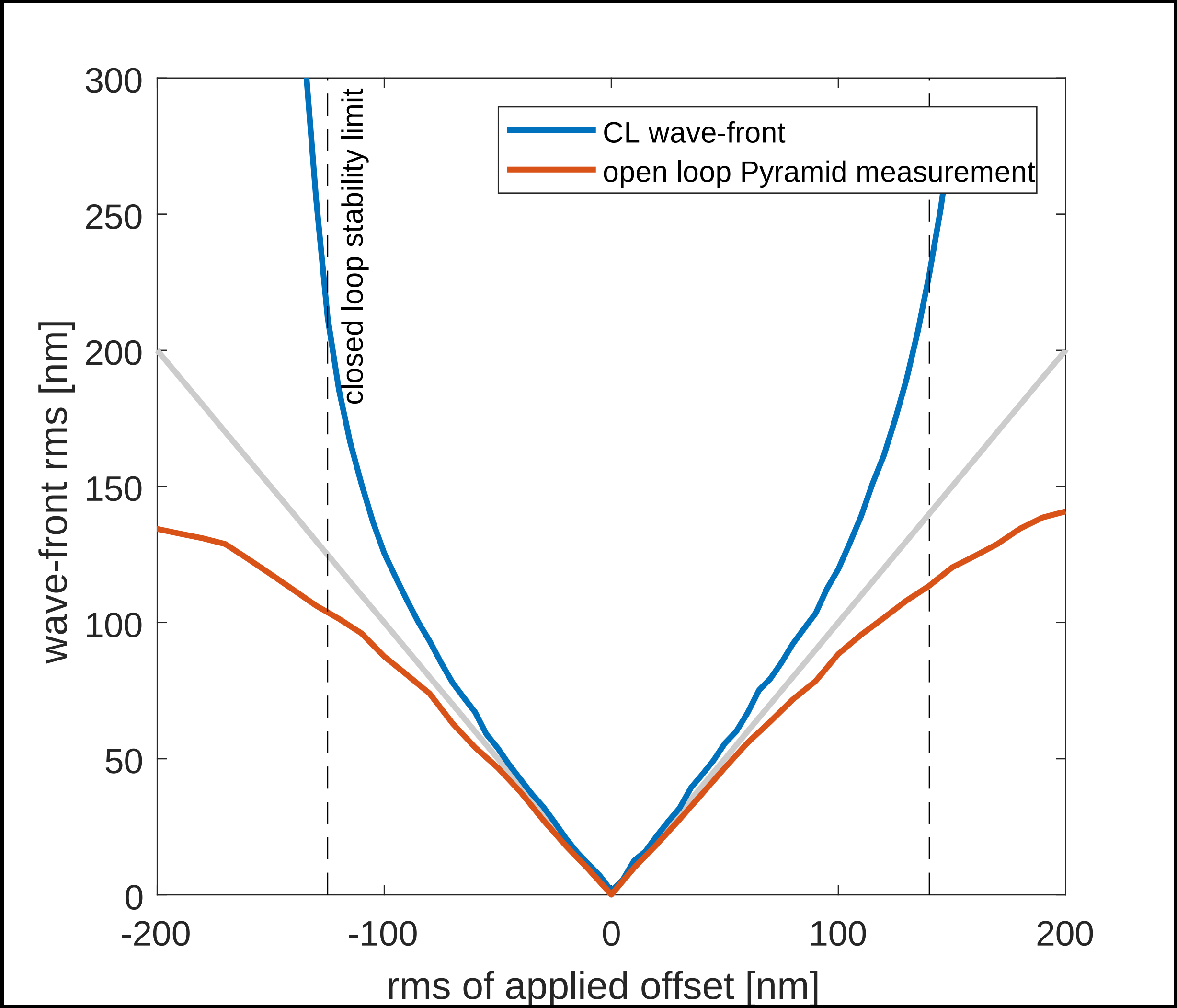


optical gain < 1

- Residual turbulence → reduced optical gain.

* Investigations into ‘gain tracking’ are ongoing. See poster P3034.

Pyramid operation with offsets

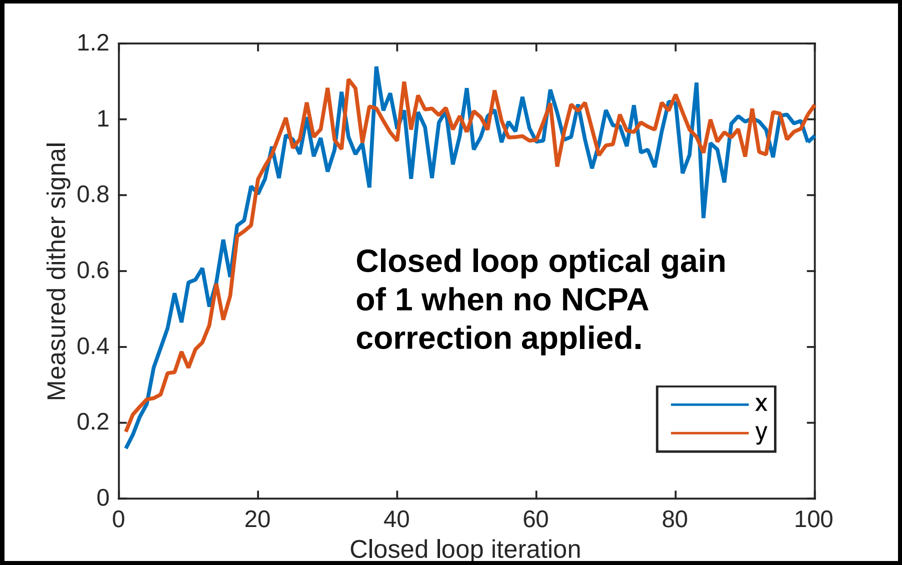


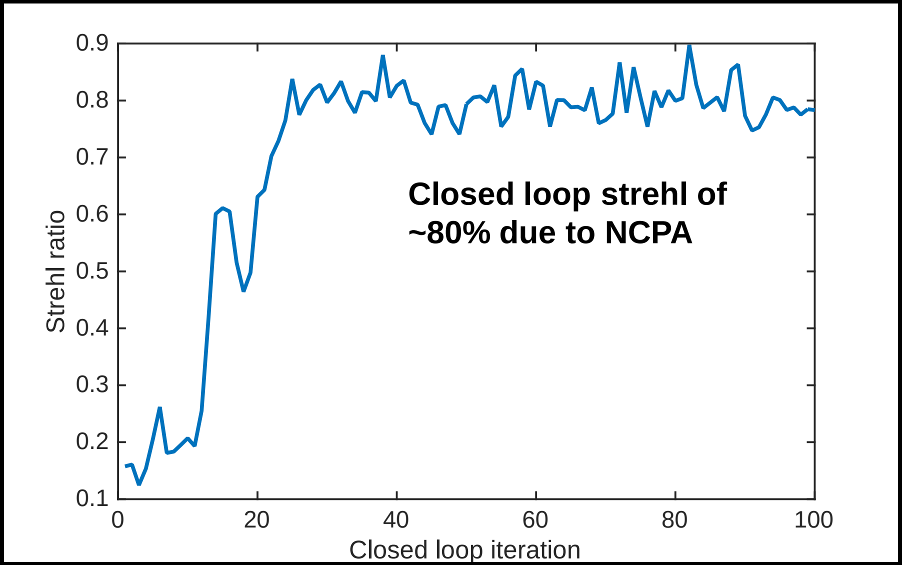
Laboratory measurement with modulation = 1λ/D and focus offset applied.

- NCPA in the AO system requires the WFS to work with an offset.
- Tight linear range restricts the NCPA which can be accurately corrected.
- Applying an offset far from the linear range can destabilise the closed loop.

Tracking the optical gain at the HIA

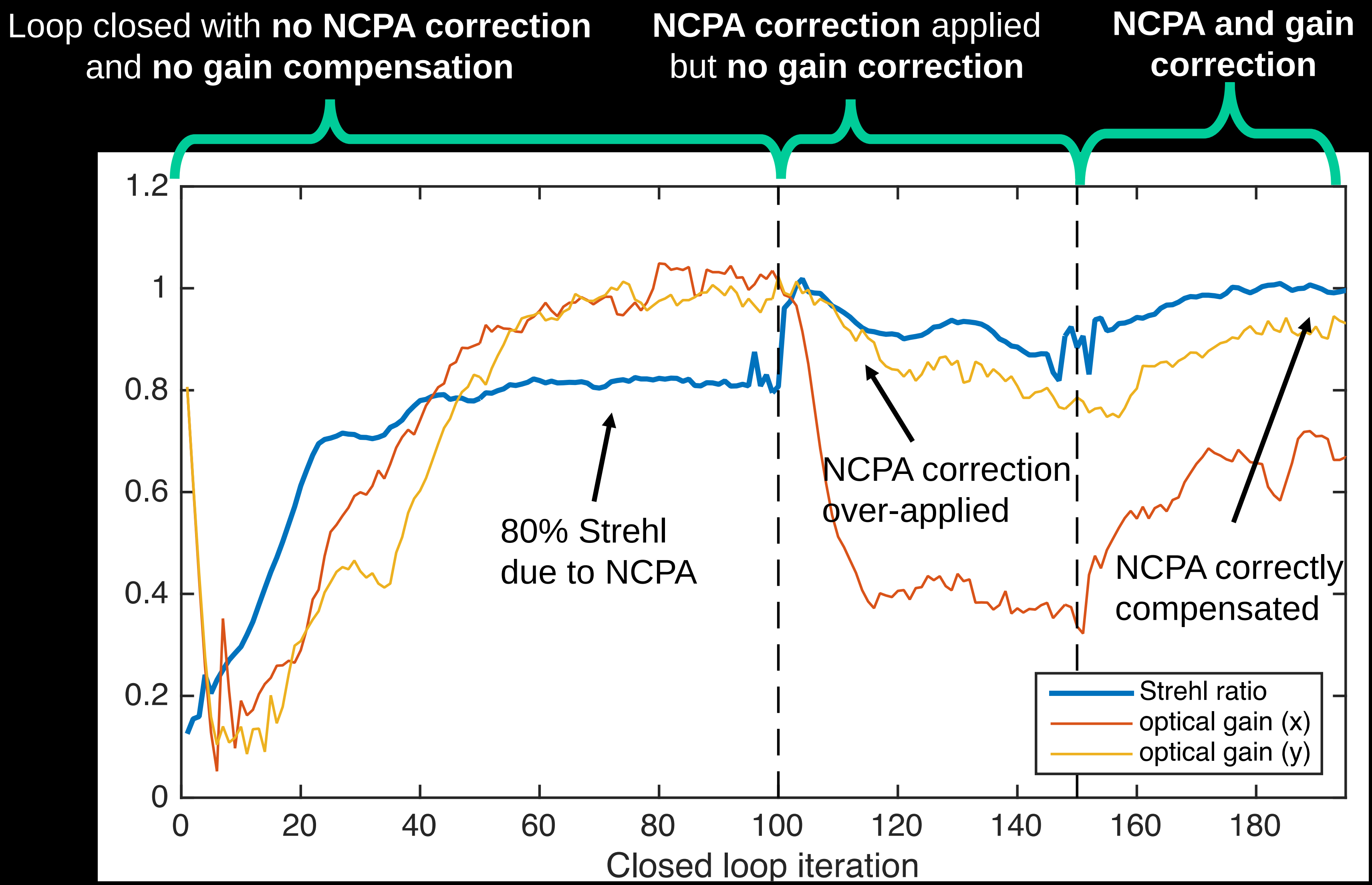
- Gain tracking carried out on HIA Pyramid bench in Victoria, Canada.
- Known signal injected into system via modulation mirror.
- Non-common path aberrations: **~80 nm rms (astigmatism + focus).**





Measurements of the optical gain (left) and Strehl (right) as the loop is closed.

Compensation of the optical gain



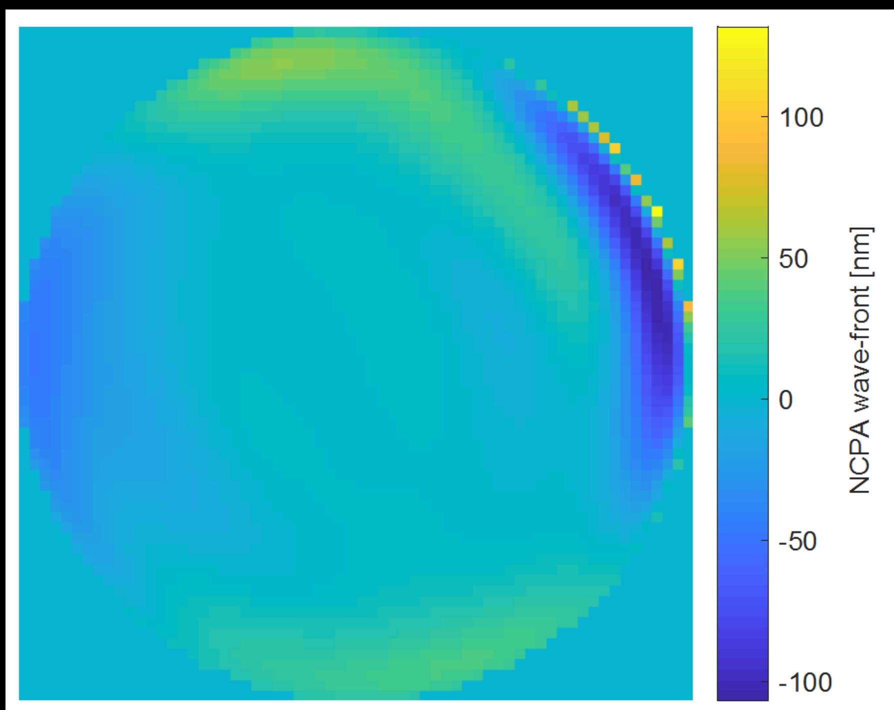
Strehl ratio and optical gain as the loop is closed and NCPA and gain correction are applied.

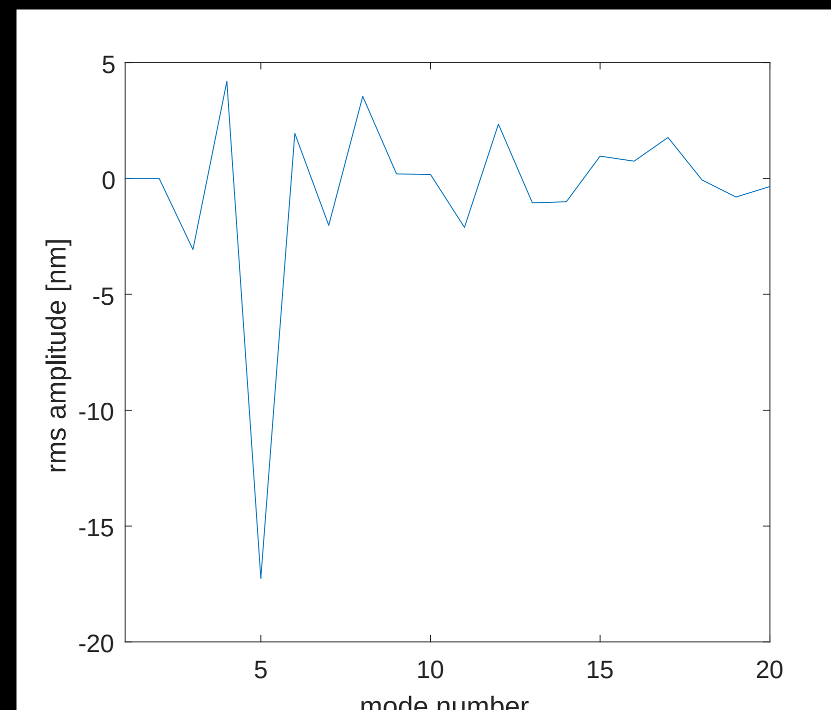
* See poster P3034.

Dynamic performance and comparison with model

NCPA estimation on the bench

- Phase diversity implemented to estimate NCPA on LAM bench.
- Reference Strehl improvement from 85% to 97%.





Estimated NCPA between imaging camera and Pyramid WFS of ~25 nm rms.

Closing the loop with turbulence

Closed loop example:

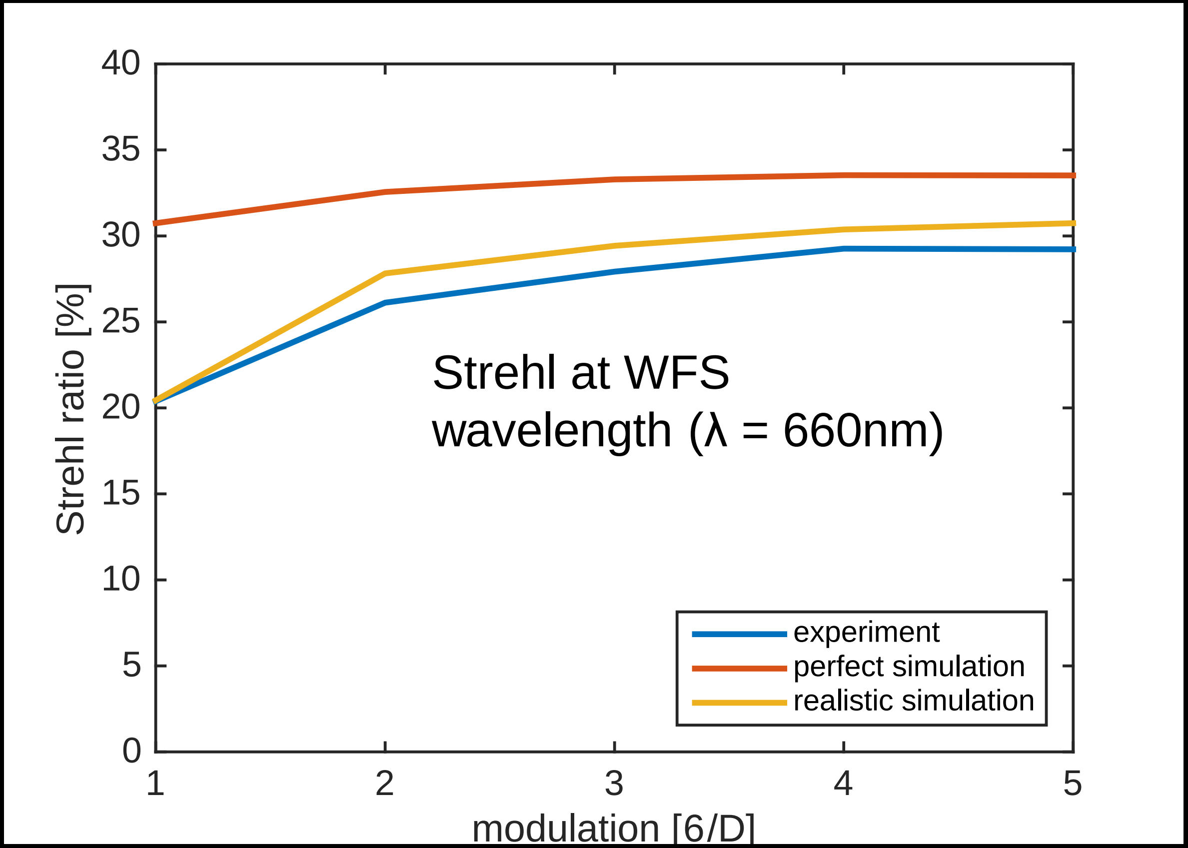
- **4 λ/D modulation**
- **Turbulence with $d/r_0 = 3.2$**

Long exposure image

29% Strehl
(λ = 660 nm)

Analysis of closed loop performance

- Modulation improves performance (larger linear range).
- Loop gain optimised in experiment for maximum Strehl.
- Good agreement with simulation.
- Realistic model includes:
  - Roof-top
  - NCPA
  - Modes projected on DM.



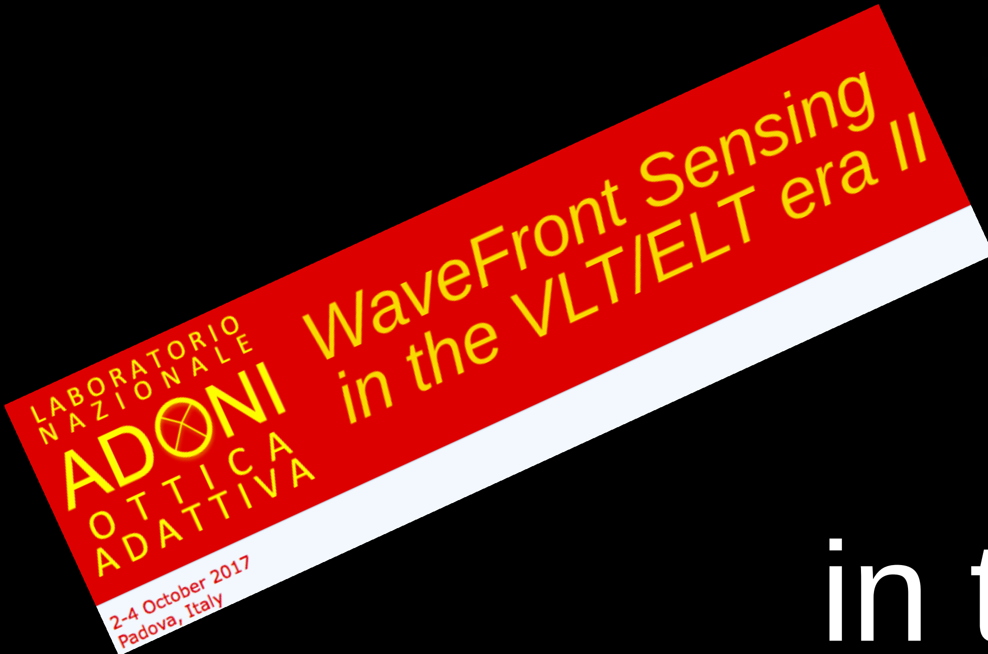
Conclusions and outlook

Lessons learnt

- Calibration: good agreement with models.
- Pyramid WFS can be tricky in non-linear regime.
- Different options to correct for NCPA.
- Final bench performance limited at low modulation (NCPA and roof-top effects).
- Error budget well understood.

Future tests

- Fourier reconstruction.
- Modal gain tracking/ ‘on sky’ calibration.
- Bench available to test new concepts.



When

2-4 Oct 2017

Where

Padova (italy)

Web site:

https://www.ict.inaf.it/indico/event/521/

(or just Google the title…)

Acknowledgements

The research leading to these results received the support of:

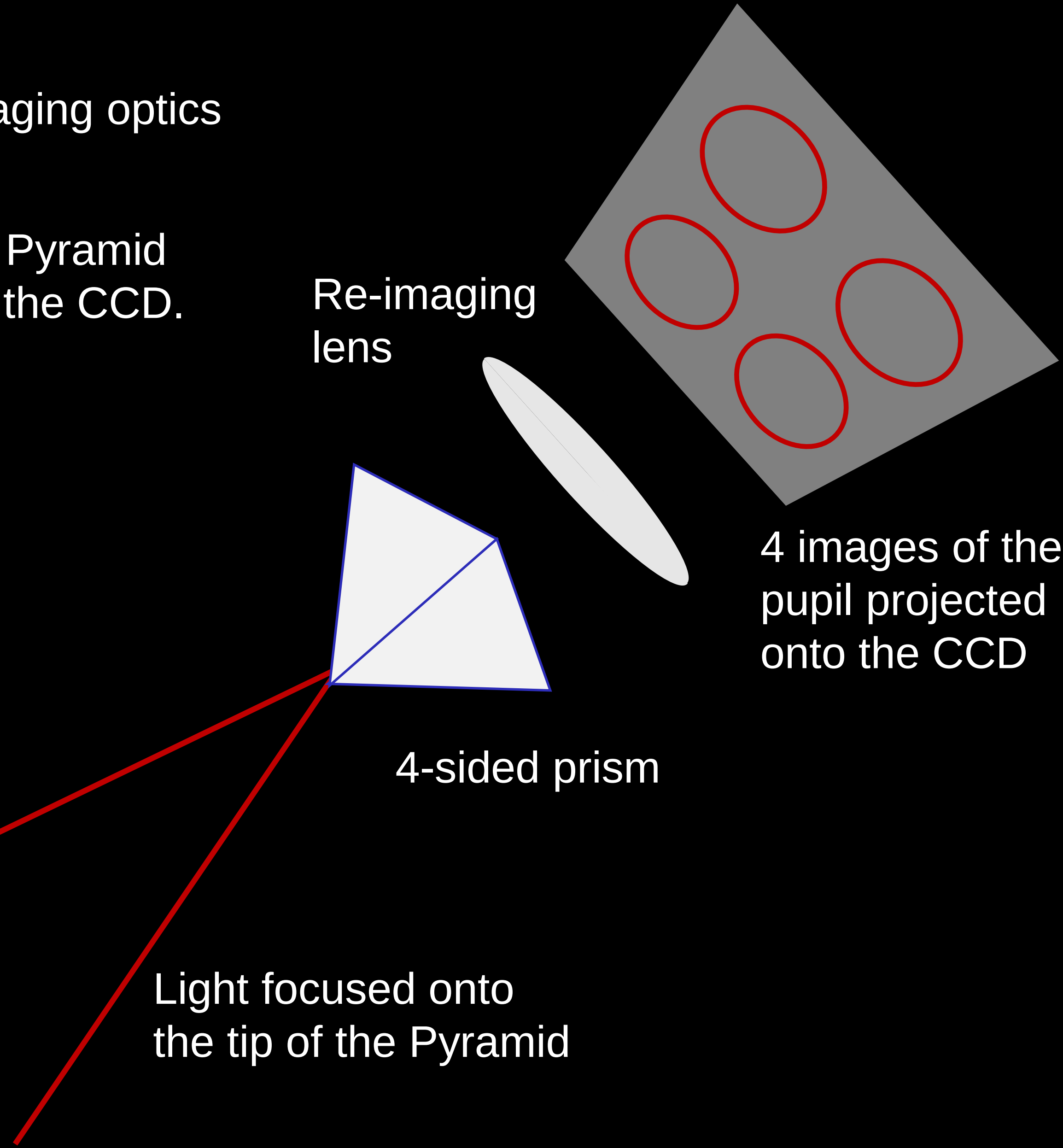
- the A*MIDEX project (no. ANR-11-IDEX-0001- 02) funded by the "Investissements d'Avenir" French Government program, managed by the French National Research Agency (ANR).
- French FUI government program, French CSAA program, French ROP network, Région PACA,
- Co-funded by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement n. PCOFUND-GA-2013-609102, through the PRESTIGE programme coordinated by Campus France.

The Pyramid wave-front sensor

- Consists of a 4-sided prism, re-imaging optics and a CCD camera.
- Light focused onto the point of the Pyramid and 4 pupil images projected onto the CCD.

Advantages over Shack-Hartmann

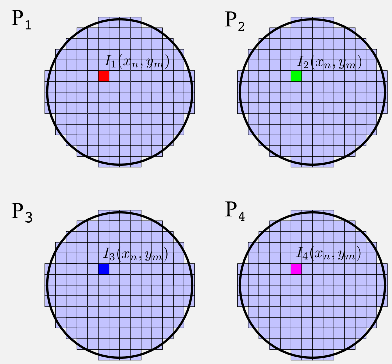
- Potential for increased sensitivity within the correction band.
- Less susceptible to aliasing.
- Flexibility: modulation allows for adjustment of linear range for different conditions.



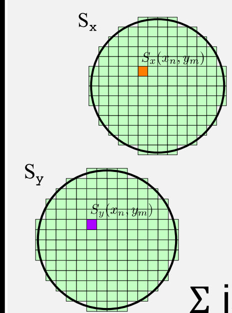
Pyramid signals

4 pupil images

- 4 pupils on the CCD camera.
- Identification of equivalent pixels in each image.



2 signal maps

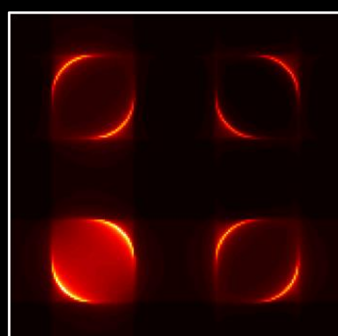


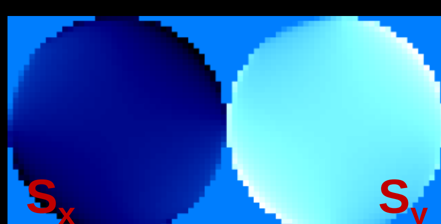
$$S_x = \frac{I_1 + I_3 - I_2 + I_4}{\Sigma}$$

$$S_y = \frac{I_1 + I_2 - I_3 + I_4}{\Sigma}$$

Σ is a normalisation term dependent on the total light on the detector.

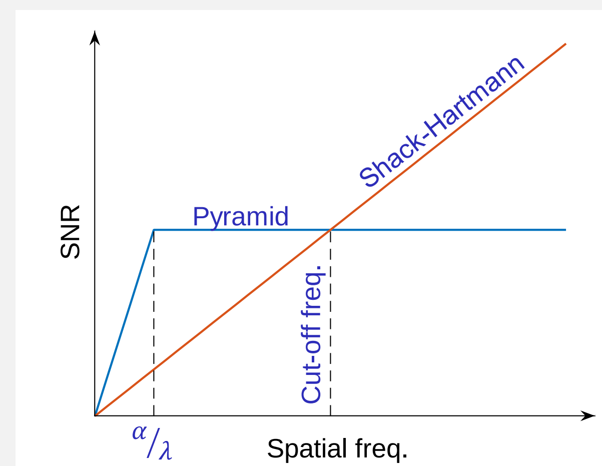
Example signals: Wave-front tilt





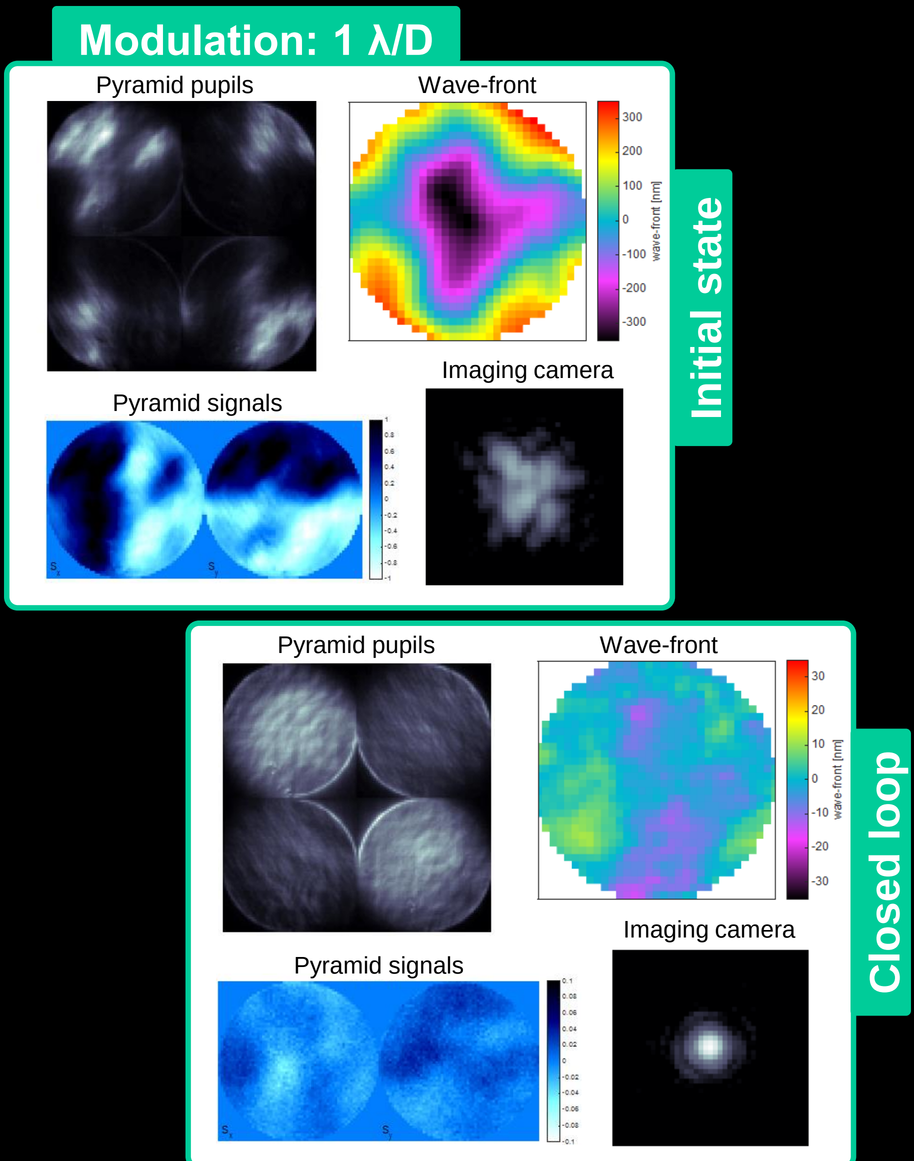
Modulation

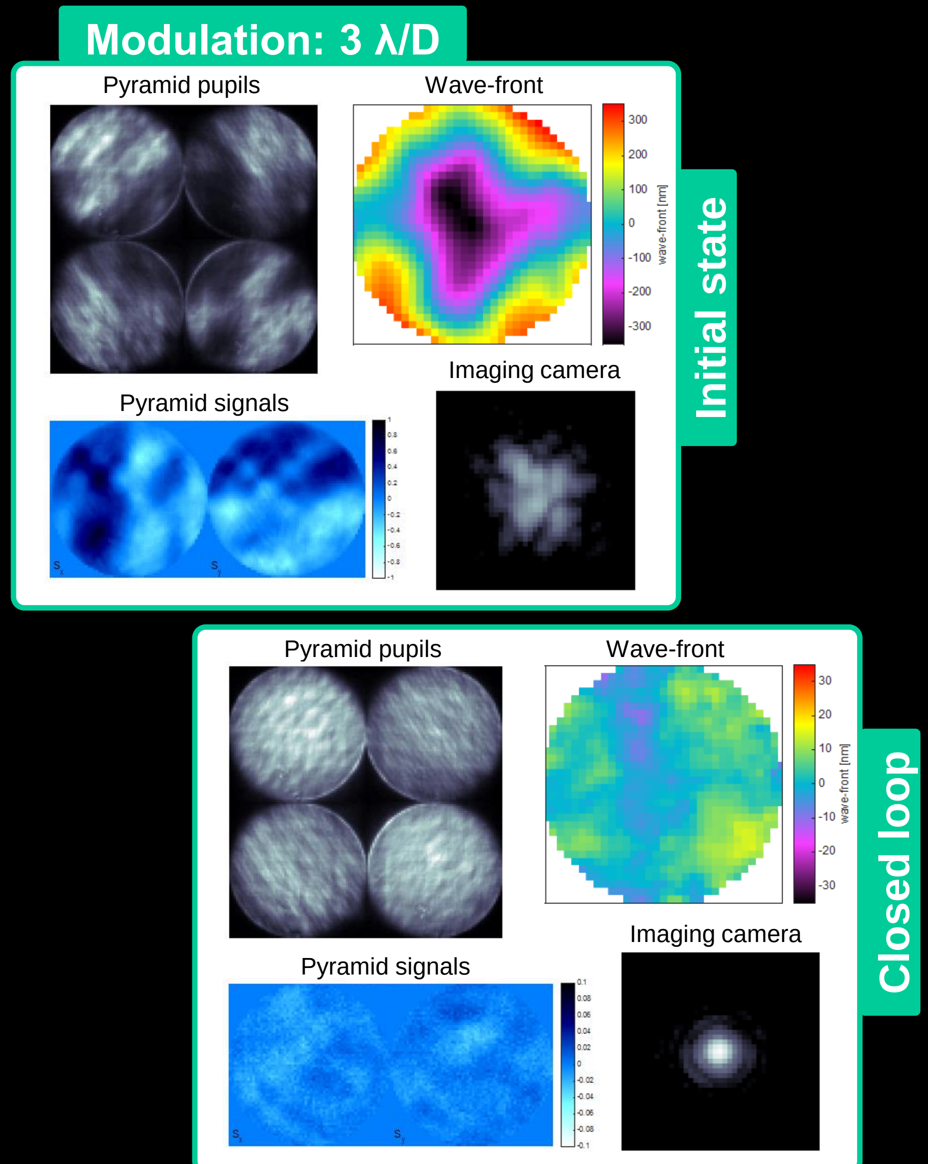
- Modulation ≈ larger spot size.
- Modulation angle $\alpha = m\frac{\lambda}{D}$
- Larger linear range vs. reduction in sensitivity at some spatial frequencies.



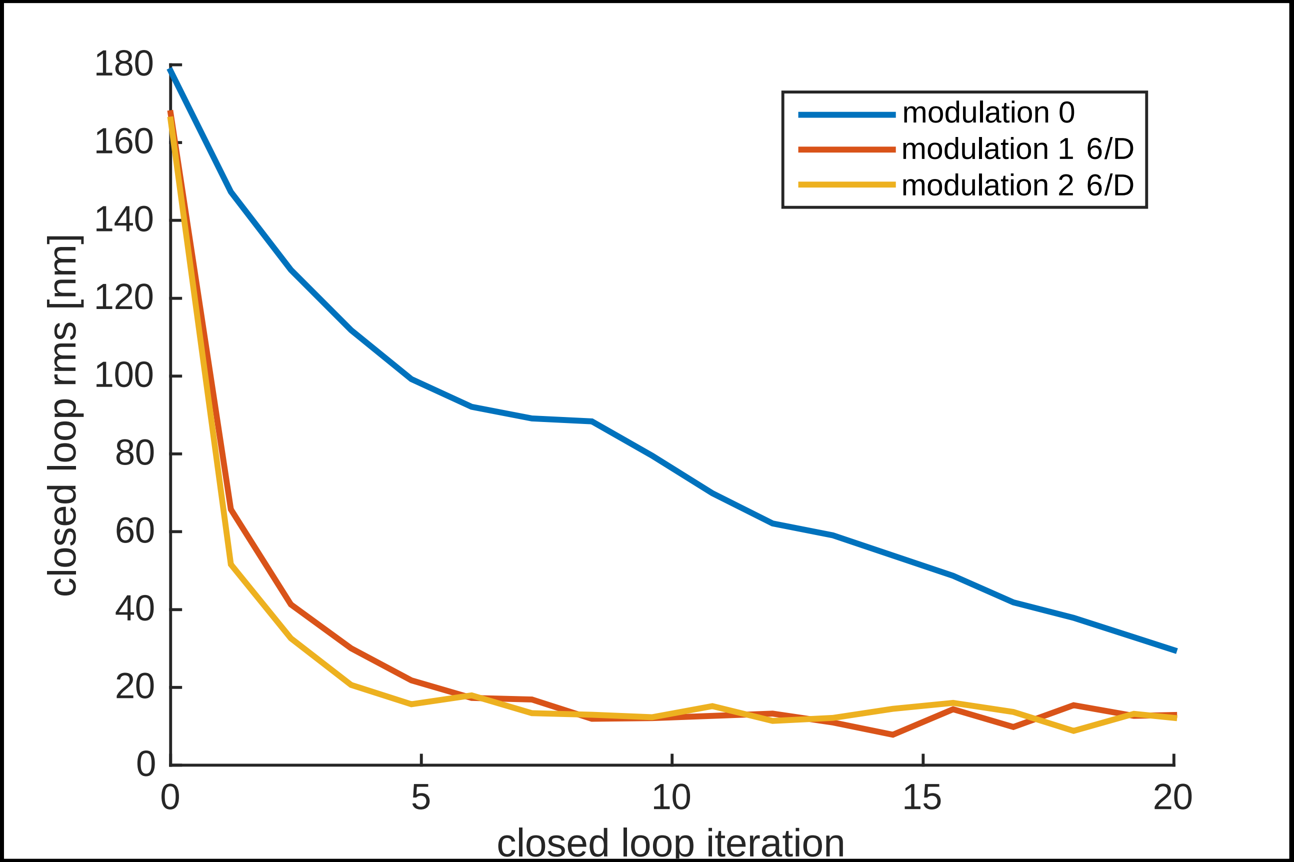
Increasing modulation →

Closing the loop: no turbulence





Closing the loop: static distortions



- A small modulation increases the linear range.
- Modulating achieves a much quicker correction.

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
extra
Aix*Marseille université
A*Midex Initiative d'excellence Aix-Marseille