Science & Technology Facilities Council
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Sensing and control of segmented mirrors with a Pyramid wavefront sensor

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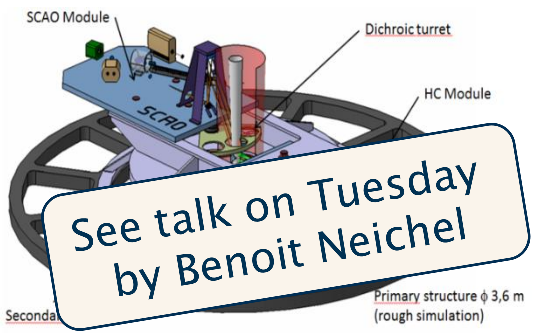
Context of study: HARMONI & ELT

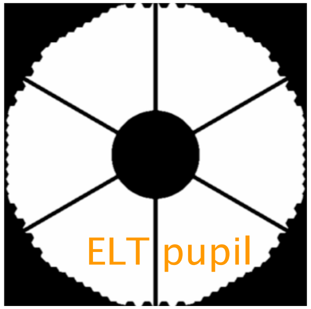
HARMONI

- SCAO system analysis
  - 100x100 PYR WFS @ 500 Hz, in I-Band
- Nominal seeing
  - 0.65'' (r0≈15cm), 30º zenith, high flux



Segmented deformable mirror (M4)

- Segmented thin shell made of 6 discontinuous petals
- Petals have a common reference body



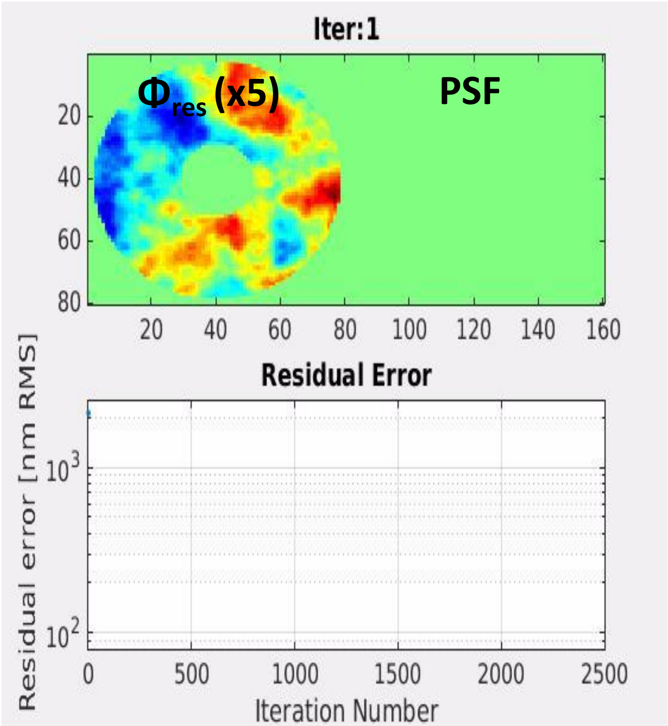
Secondary mirror unit: Spiders

- Supported by six 50 cm wide spiders > r0
- Matching the 6-petal geometry
- One PYR pixel is 37cm (D/100) < 50cm

Motivation: Impact of large spiders & M4

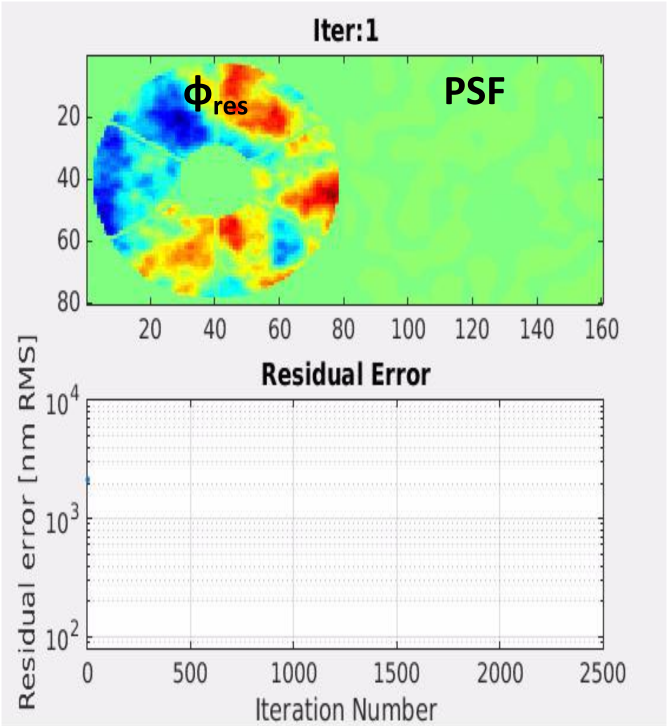
No spiders & continuous DM

- Good performance (pure AO perf.)
  - 101 nm RMS residual error
- Good stability
  - ± 4 nm



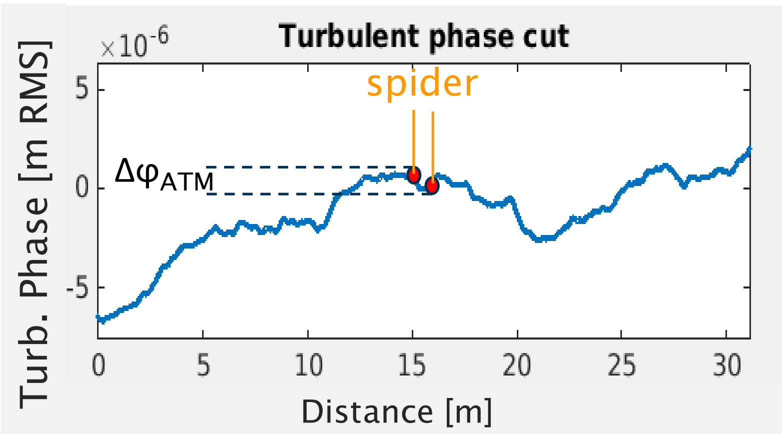
Spiders & M4

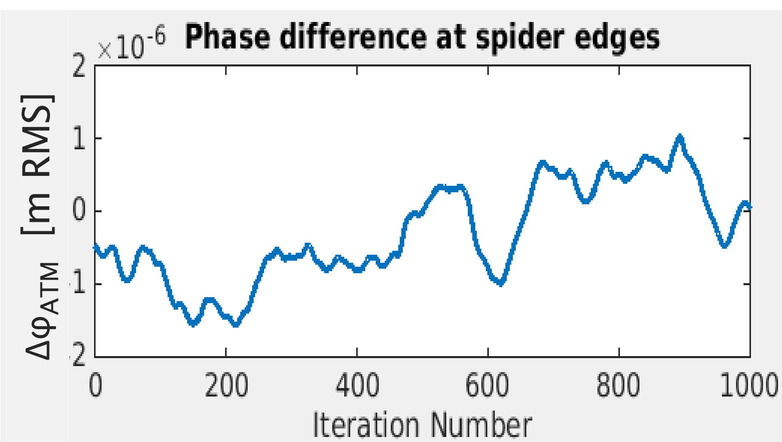
- Very poor performance
  - >5000 nm RMS res. error
  - Additional differential piston between petals > ±7 waves



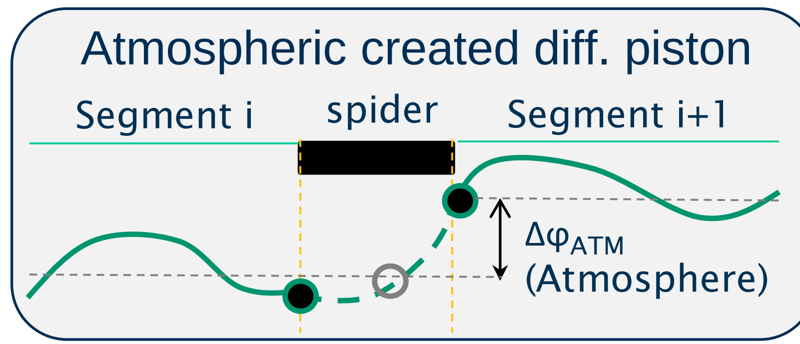
Differential piston: Atmosphere + Islands

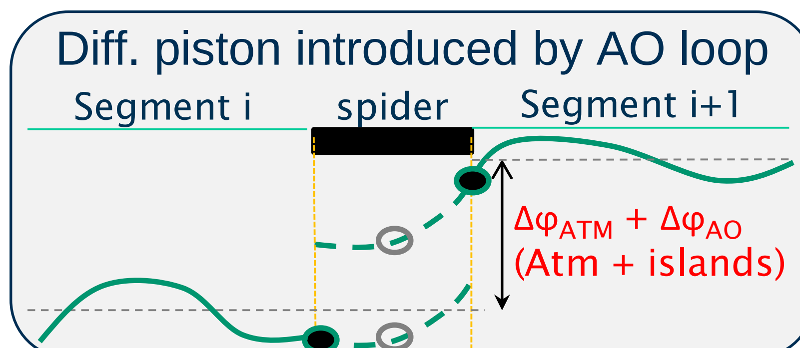
- Differential piston is present in atmospheric turbulence





- For large gaps, differential piston not well sensed by the WFS
  - PYR or SH
  - π ambiguity (λ jumps)
- Additional unwanted term is injected by AO loop

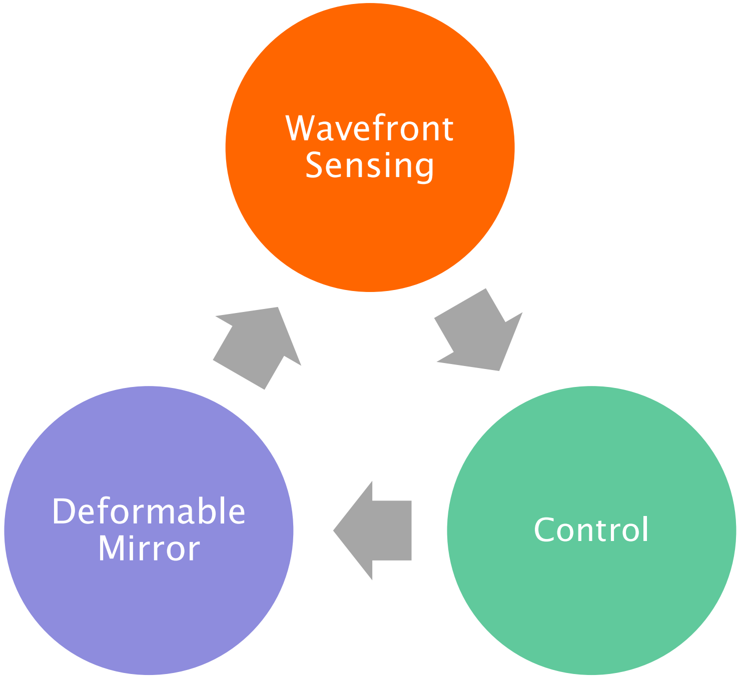




Handling differential pistons

- Provide a simple solution to
  - Remove diff. pistons in the presence of turbulence ($\Delta\phi_{AO}$)
  - Correct atmospheric differential pistons ($\Delta\phi_{ATM}$)
- $\Delta\phi_{AO}$ & $\Delta\phi_{ATM}$ are of the same order of magnitude
  - Hard to disentangle
- SCAO error budget study
  - 70nm RMS of additional diff. piston is acceptable to meet specifications (in quadrature)

Differential piston is an AO related issue

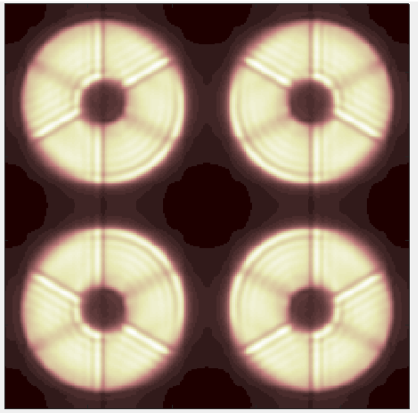


Handling differential pistons: WFS

- Existing solution: add another WFS
  - ➢ Differential piston can be sensed modulo λ
  - ➢ WFS_1 at λ & WFS_2 at λ+Δλ
  - ➢ Increased cost and complexity!

See talks this afternoon:
➢ Fernando Quiros (GMT)

- Crazy ideas (for HARMONI)
  - ➢ WFSing at longer λ to have spider width ≤ r0.
    - Detector in K-Band? + Using science photons!
  - ➢ Add information under the footprints of the spiders
    - Fourier extrapolation
    - Defocusing the WFS
    - ➔Phase on either side of spiders is decorrelated: Cannot create correct information



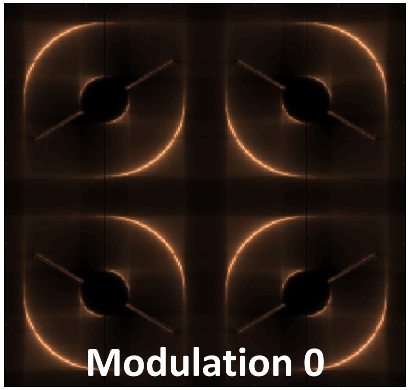
Defocused the WFS to spread information under the spiders

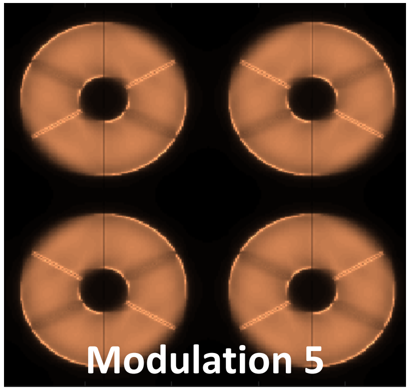
Charlotte Z. Bond et al., "Iterative wave-front reconstruction in the Fourier domain," Opt. Express 25, (2017)

Handling differential pistons: WFS

- Valid detector pixels & modulation
  - Useful signal is contained in the diffracted light
    - Include region under the spiders' shadow
  - Diffracted light outside the pupil footprint comes with small modulation
    - Keep modulation as small as possible
    - Choice: 3 or 5λ/D
  - Gaps=0.5m & pixels=0.37m (D/100)
    - Little signal is present!
  - It's a prerequisite but it's insufficient

Illuminated PYR pixels





C. Vérinaud and S. Esposito, "Adaptive-optics correction of a stellar interferometer with a single pyramid wave-front sensor," Opt. Lett. 27, 470-472 (2002)
Pinna et al, "Why not use the pyramid to phase your ELT?", Wavefront Sensing in the VLT/ELT era, Marseille (2016)

Removing diff. piston from commands

- Filtering out segment pistons in correction phase
  - Atmosphere contains segment pistons ($\Delta\phi_{ATM}$)
  - Leads to truncated correction phase & ultimately poor performance
- Penalty on the commands
  - $c = (M^TM+\alpha V^TV)^{-1}M^Ts$. V contains the mode to be rejected such that $v_i^Tc<\varepsilon$
  - The α parameter allows for selectivity and trade-off
  - We can penalise 1st derivatives, curvature, step at the DM edges etc.
  - Difficult trade-off that might change from frame to frame
- Relying on prior information
  - Use pseudo-open loop control
  - Rely on phase spatial statistics to smooth the DM commands
  - Initial results are not conclusive. Work in progress!

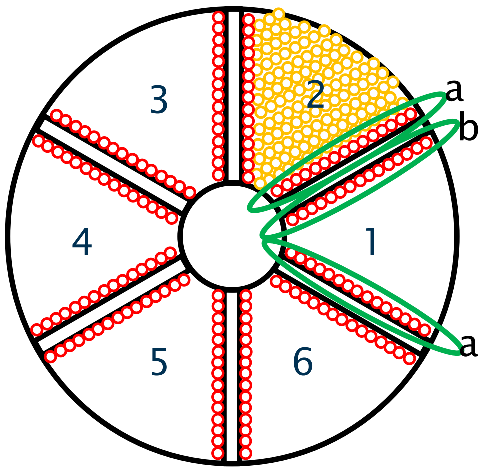
Phase closure: Estimating the diff. piston

Method

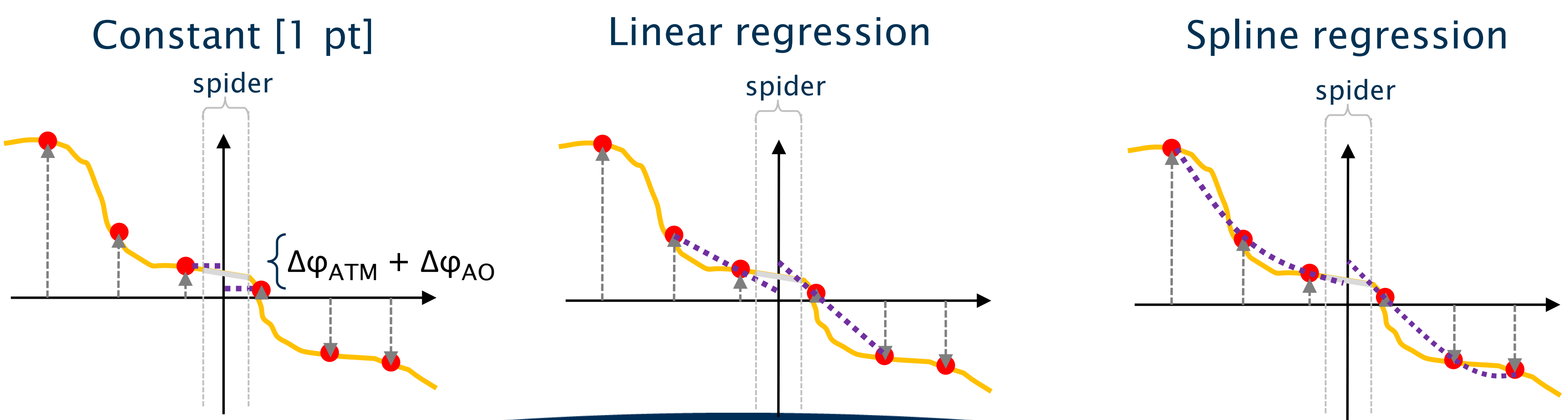
Assume piston can be extracted from edges

1. Average phase along radius at edge of segment
2. Extrapolation of turbulence in the middle of spider based on each segment phase (linear, spline…)
3. Solve linear system (6 unknowns, 6 measurements) to find piston of each segment

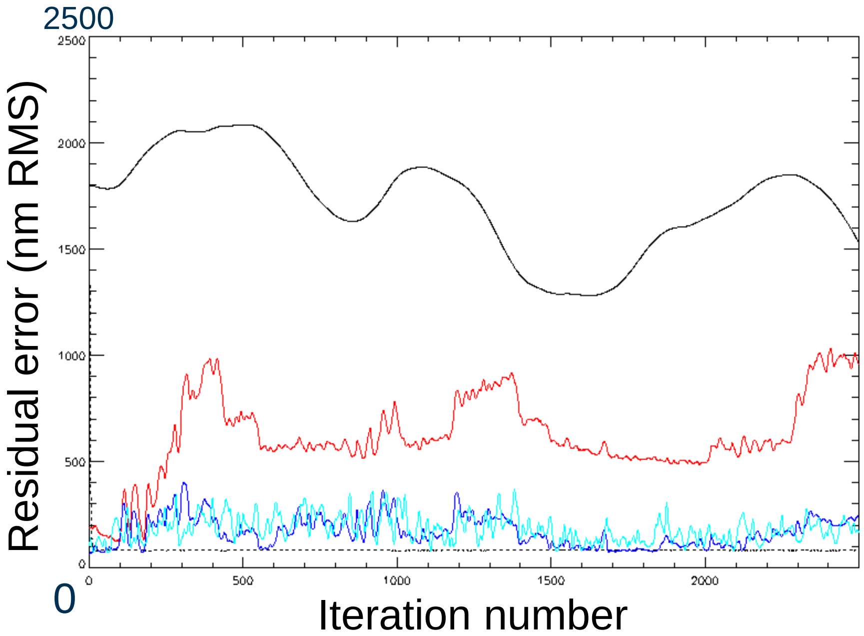
1st step: Spatial radial average



2nd step: Extrapolate piston



Phase closure: Results

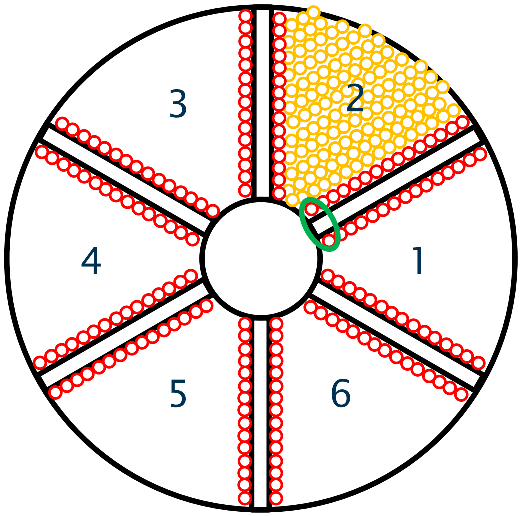


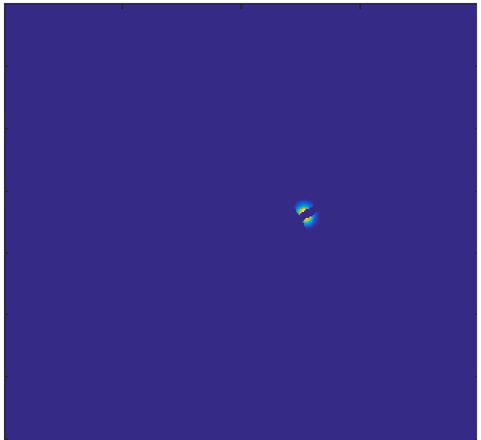
- Input turbulence
- No diff. piston handling
- Phase closure
- Phase closure (w/ moving average)
- Pure fitting error

- Clear gain observed
  - Average residual error: 165 nm RMS
  - Large variation: max 371 nm
- Data averaging methods
  - Radial averaging along edges
  - Actuator position or phase
  - With and without time averaging ($\Delta\phi_{ATM}$ has slow dynamics)
- Basic limitations of the method
  - Loss of continuity b/c gaps larger than correlation distance
  - Biased estimation of information used to ensure continuity
- Conclusion
  - Phase extrapolation + phase closure doesn't perform well enough
  - Island error: 134 nm! >> 70nm

Slaving actuators: Approach

- Goal
  - ➢ Impose continuity of the DM surface
- Approach details
  - ➢ Pair-wise coupling of edge actuators
  - ➢ Common reference body gives absolute position of the 6 DM petals
- Drawbacks
  - ➢ We loose in actuators count (162 DoF)
  - ➢ Completely negligible in error budget
    - ▪ Fitting error from 85nm to 86nm

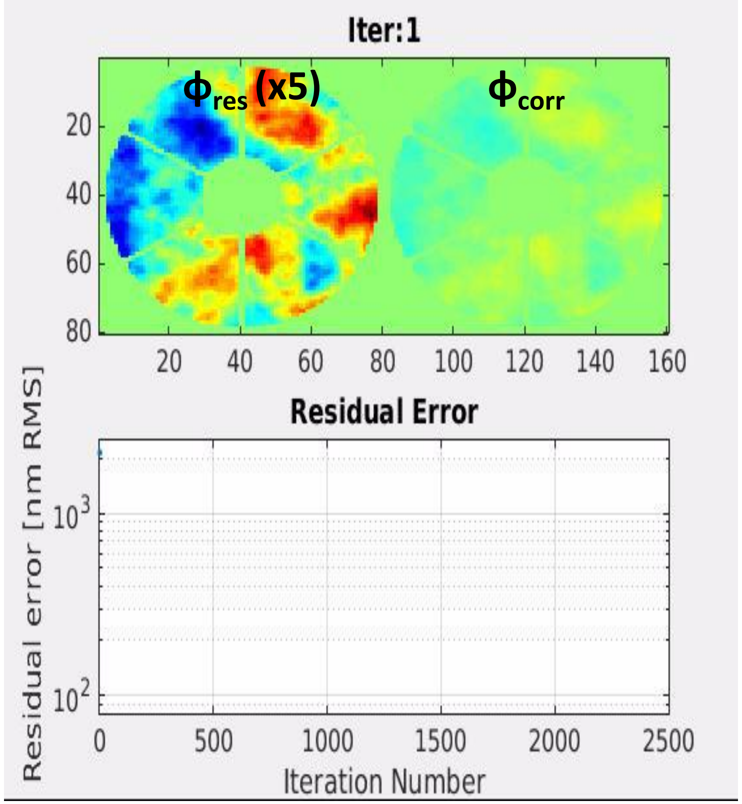




Coupled influence function

Slaving actuators: Results

- Good average performance
  - 107 nm RMS (in median seeing conditions 0.65'')
- Good stability
  - Min 100 nm & max 140 nm
- Remaining residual errors
  - The unwanted differential piston is strongly reduced but a small amount remains
  - Possible improvements
    - Currently using scalar gain: may be improved by modal gain
    - Or by combining w/ other methods



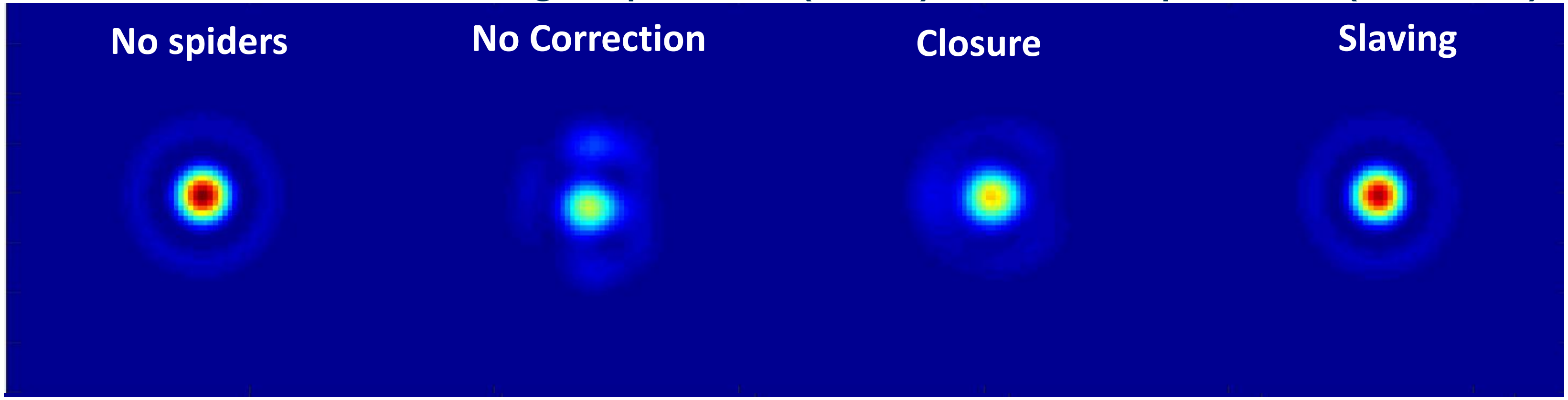
Results summary

Pure AO performance

	Average residual error	Additional error term	Strehl in K
No spiders	101 nm RMS	-	92%
No correction	> 5000 nm RMS	+ 5000 nm	0%
Regularisation	*Work in progress*	-	-
Closure	168 nm RMS	+ 134 nm	86% ✗
Slaving	107 nm RMS	+ 35 nm	91% ✓

70nm RMS additional differential piston is acceptable to meet specifications

Long exposure (5sec) PSF comparison (K-Band)



Conclusions

- Investigated both WFS and control based solutions
  - None of the WFS-only solutions are conclusive on their own.
  - We tried several methods ensuring the continuity of the phase across the pupil → Doesn't deliver the required correction levels.
  - Regularisation is still work in progress
- We propose a simple and robust solution
  - It relies on position/voltage control (i.e. slaving the edge actuators) combined with a small PYR modulation
  - It relies on knowing the absolute position of the 6 DM petals (ref. body)
  - Works for SCAO, to be demonstrated for LTAO
- Remaining work
  - Improvements
    - Combine with optimal modal gain for an optimal control of the filtered modes
    - Ensure solution compatible with a force actuators
  - Further analysis
    - How does the correction performs as a function of seeing?
    - Performance as a function of SNR (NGS magnitude)