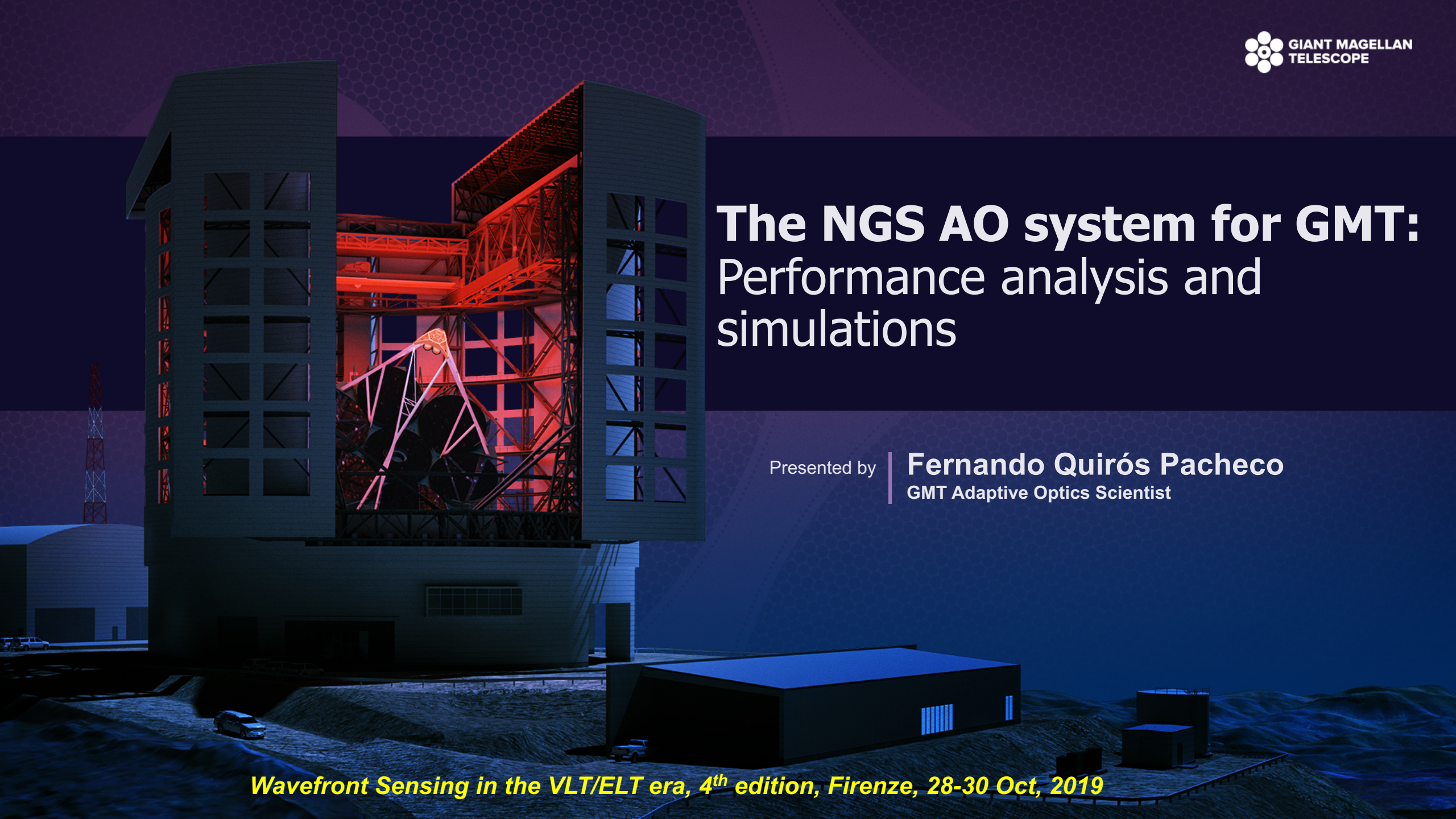
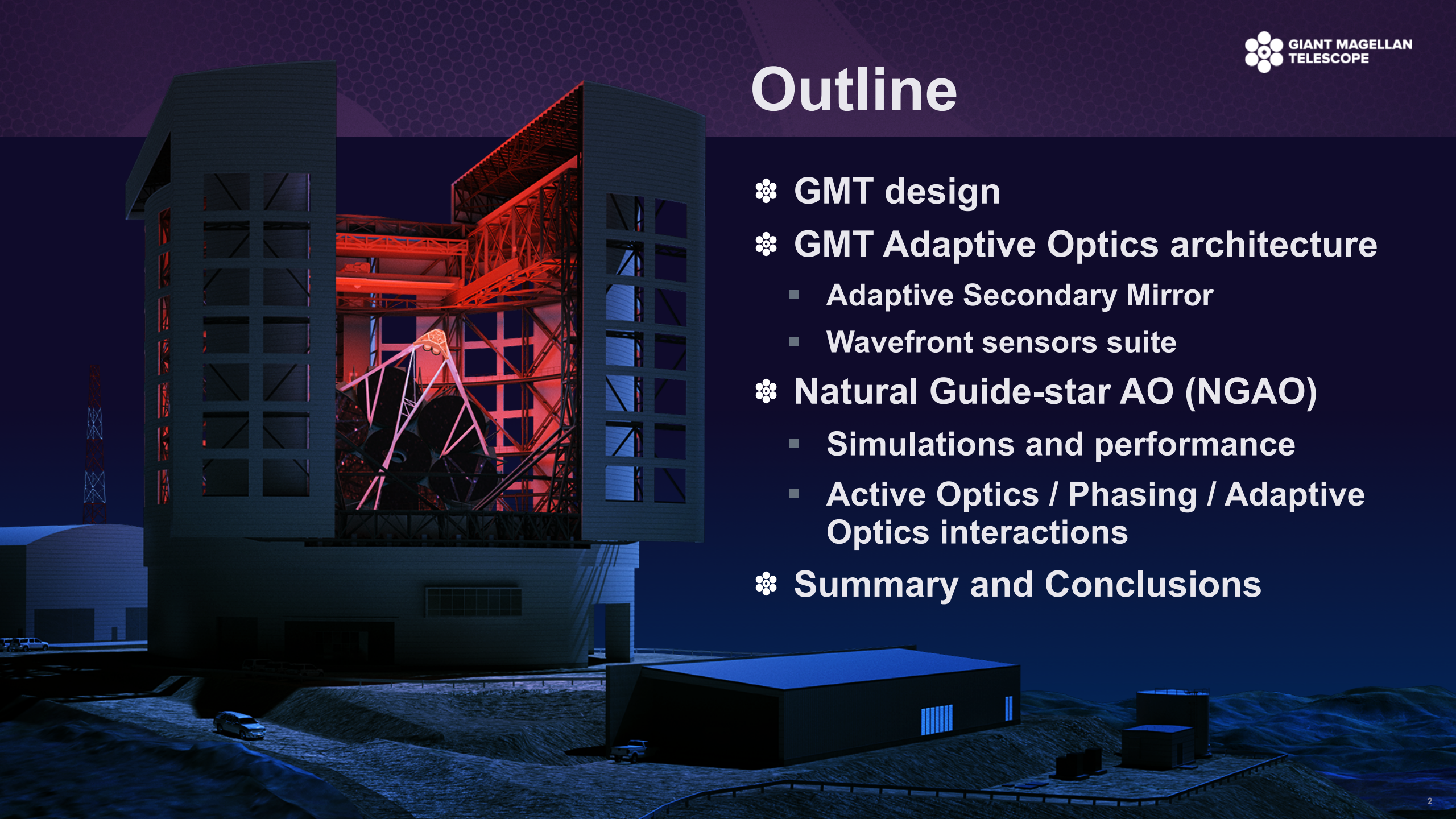


GIANT MAGELLAN TELESCOPE

The NGS AO system for GMT: Performance analysis and simulations

Presented by | **Fernando Quirós Pacheco**
GMT Adaptive Optics Scientist

Wavefront Sensing in the VLT/ELT era, 4th edition, Firenze, 28-30 Oct, 2019

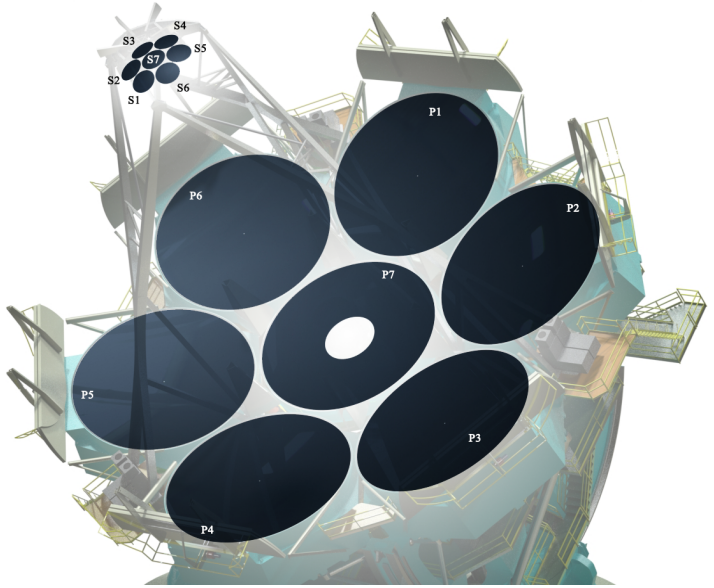


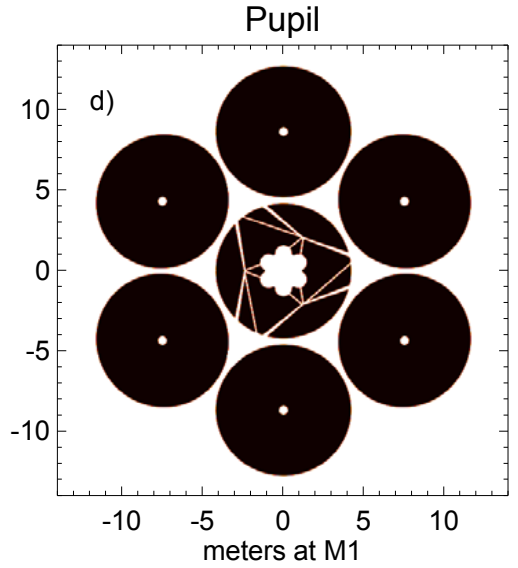
Outline

- GMT design
- GMT Adaptive Optics architecture
  - Adaptive Secondary Mirror
  - Wavefront sensors suite
- Natural Guide-star AO (NGAO)
  - Simulations and performance
  - Active Optics / Phasing / Adaptive Optics interactions
- Summary and Conclusions

The Giant Magellan Telescope (GMT)

- 24.5m diameter primary aperture
  - 362 m^2 collecting area
  - M2 conjugated at ~160 meters
- Doubly segmented design:
  - 7 x 8.4 m M1 segments (largest practical segments)
  - 7 x 1.1 m M2 segments
  - Segment gaps:
    - 40.8 cm between central and outer segments
    - 34.5 cm between outer segments





GMT Adaptive Optics Architecture

- The GMT AO uses an Adaptive Secondary Mirror (ASM) and a standardized set of wavefront sensors:
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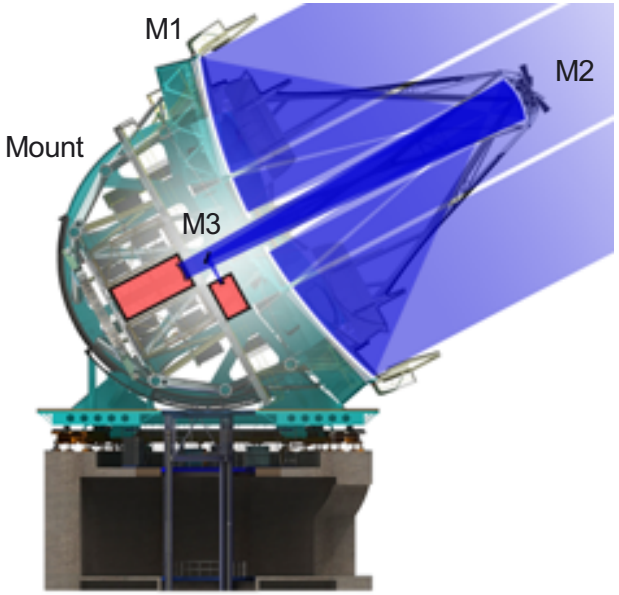
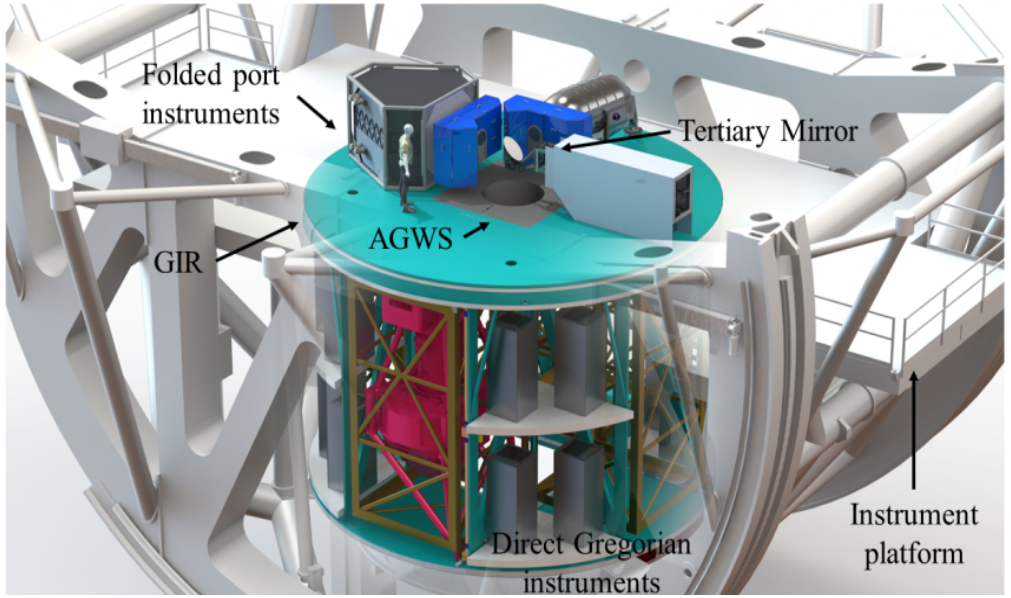
  - On-Instrument WFS (OIWFS)

  ] Replicated for each instrument





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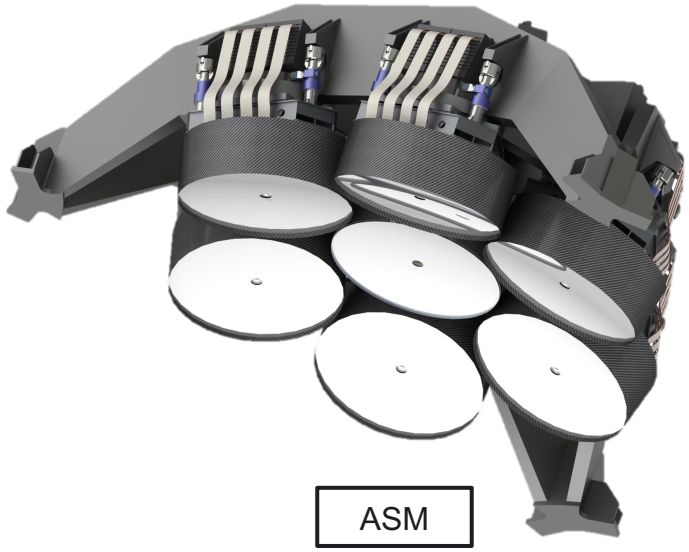
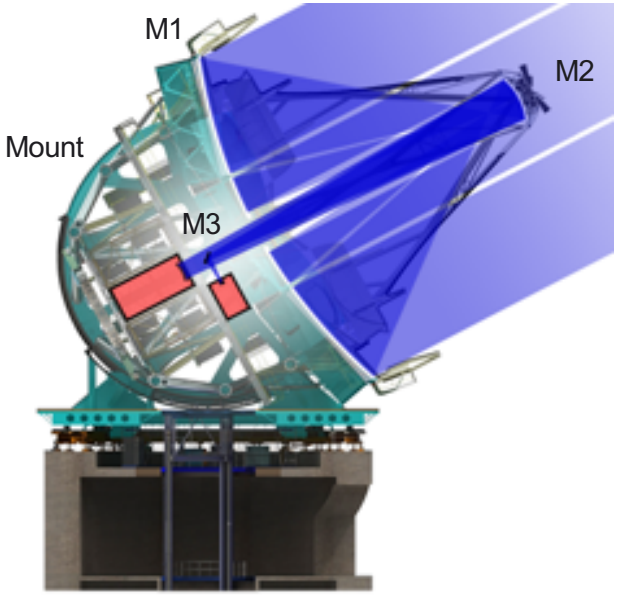
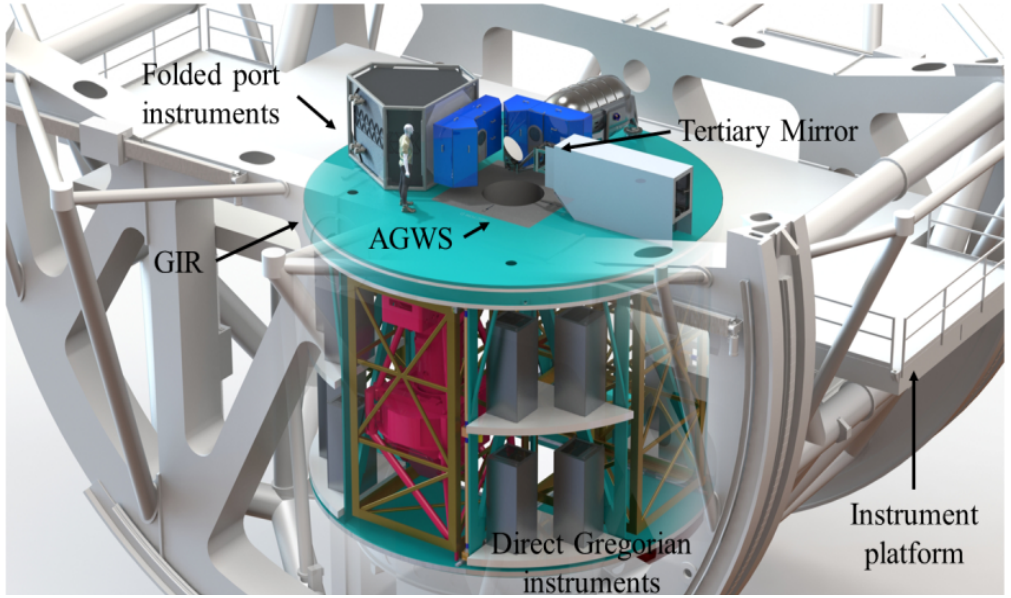
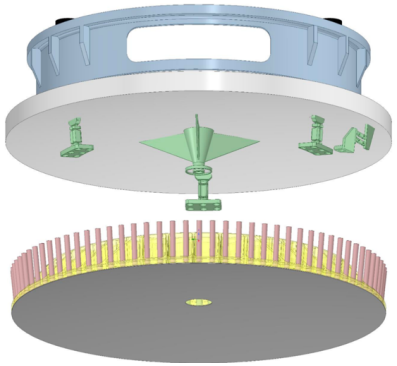


ASM







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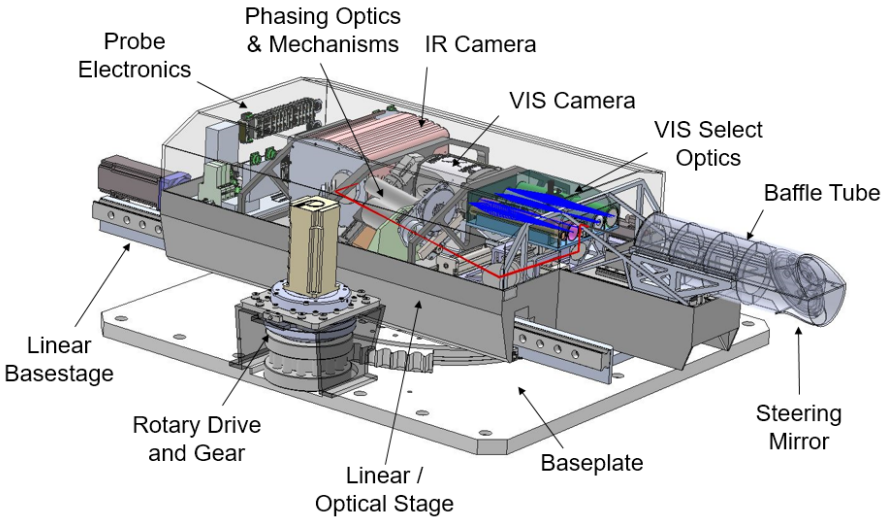

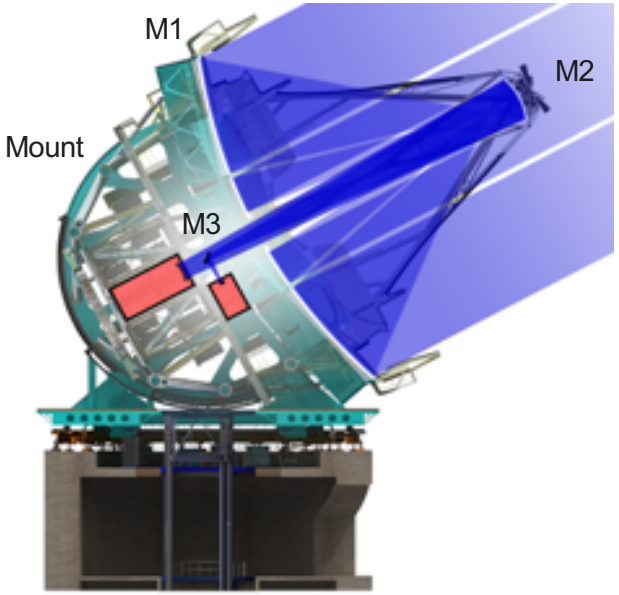

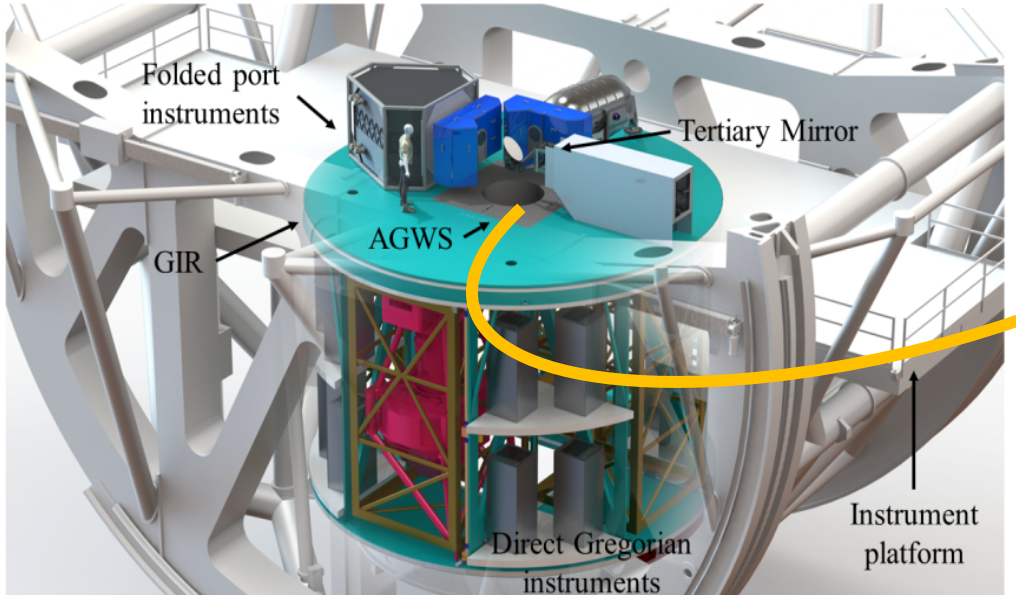

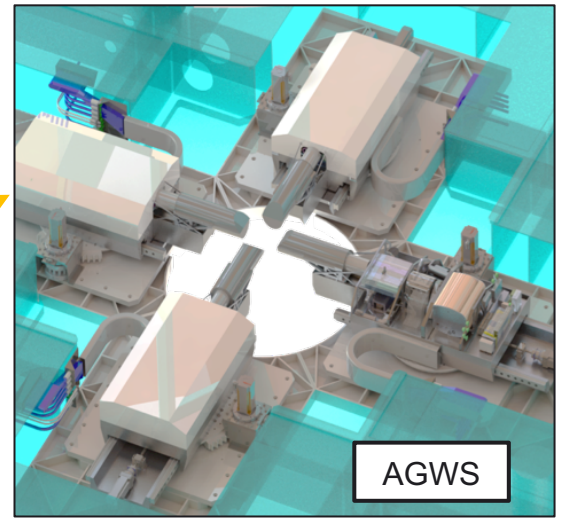

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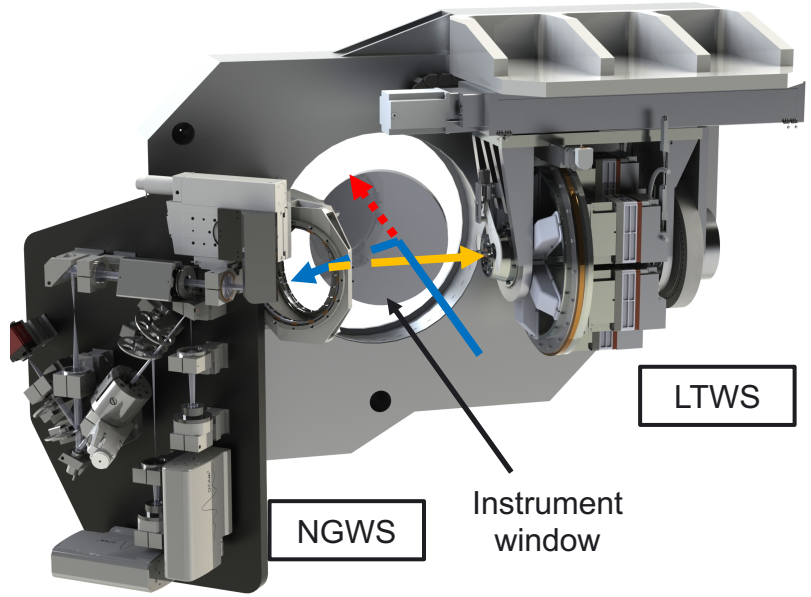

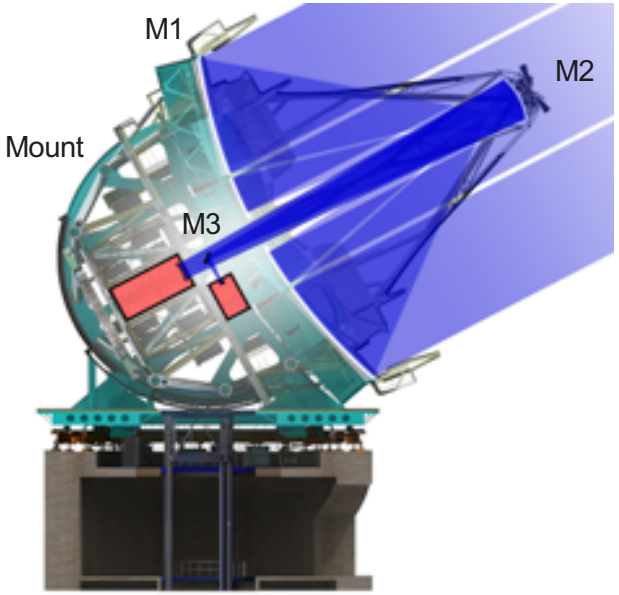

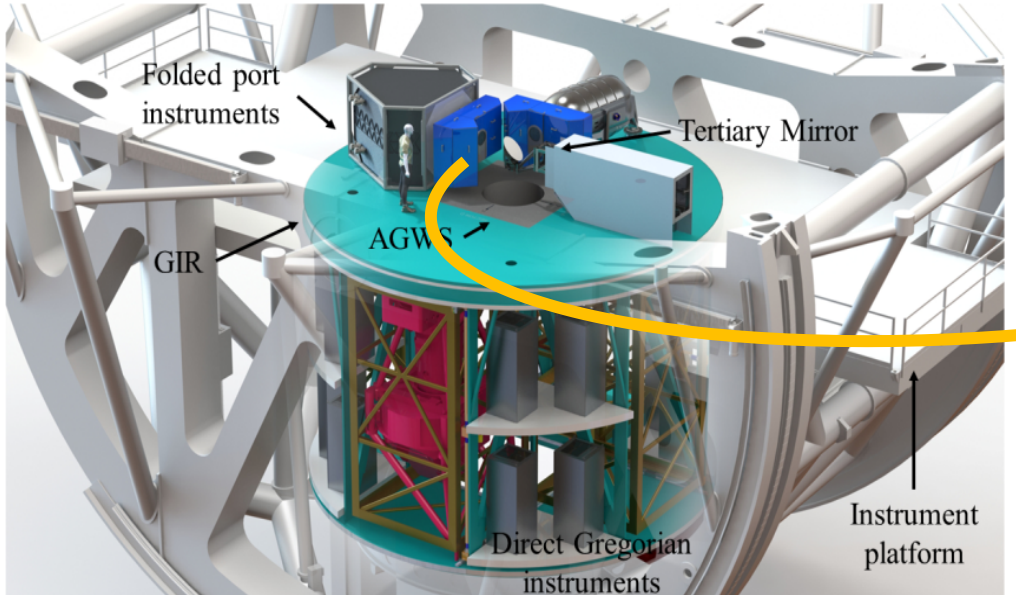

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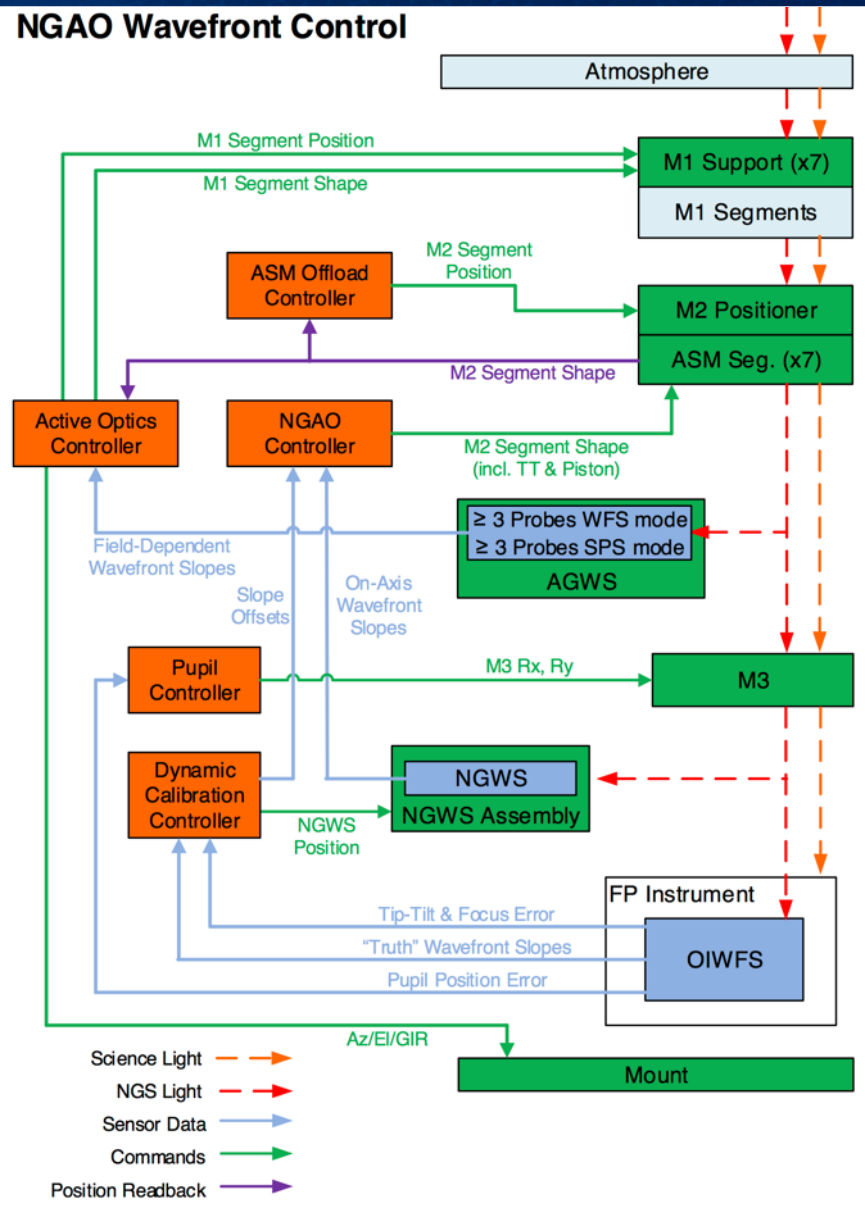
  Replicated for each instrument

- In Natural Guide Star AO (NGAO) mode:
  - AGWS controls telescope pointing, collimation, M1 figure
  - AGWS also provides initial phasing to 50 nm RMS
  - NGWS controls on-axis WFE, including segment phasing
  - OIWFS controls changing non-common path errors, M3 tip-tilt

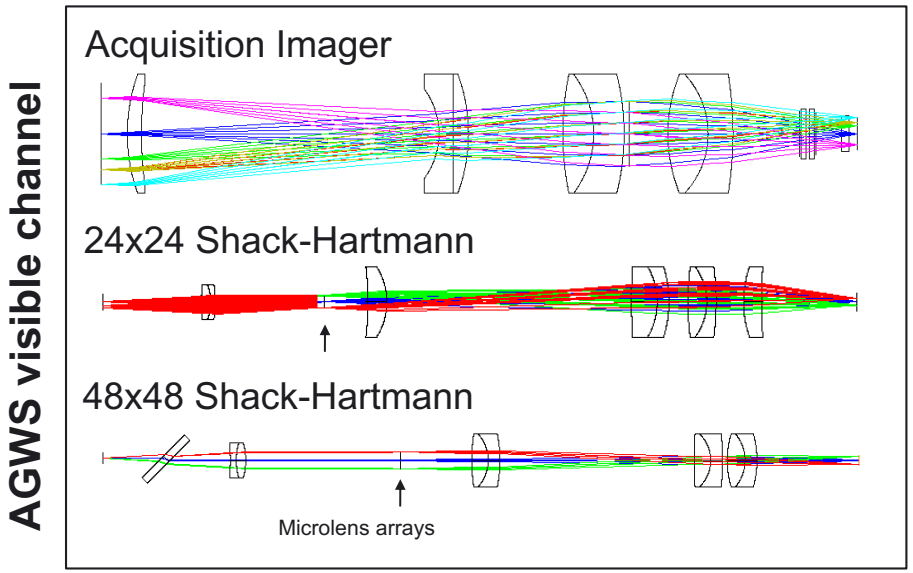
- In the Laser Tomography AO (LTAO) mode:
  - Analogous, except that LTWS does not control segment phasing



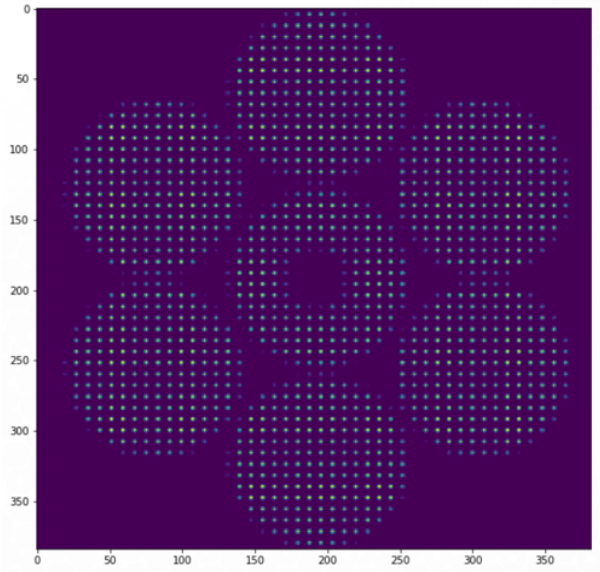
GMT Adaptive Optics Architecture
Acquisition, Guiding, and Wavefront Sensing System (AGWS)

Function	WFS type	Description	*Band* / Detector
Acquisition	30”x30” Imager	Establishes and updates the pointing of the telescope at each slew.	*R+I band* Princeton ProEM-1KBX3
Active Optics WFS	24x24 SH 48x48 SH	Provides feedback for collimation and M1 figure control.	
GLAO WFS		Provides ground layer turbulence measurement using 4 off-axis NGS	
Segment phasing Sensing (SPS)	Dispersed Fringe Sensor	Measures piston error between different M1/M2 segment pairs.	*J band* C-Red One

Selectable optical configurations



WFS spot pattern 48x48 SH



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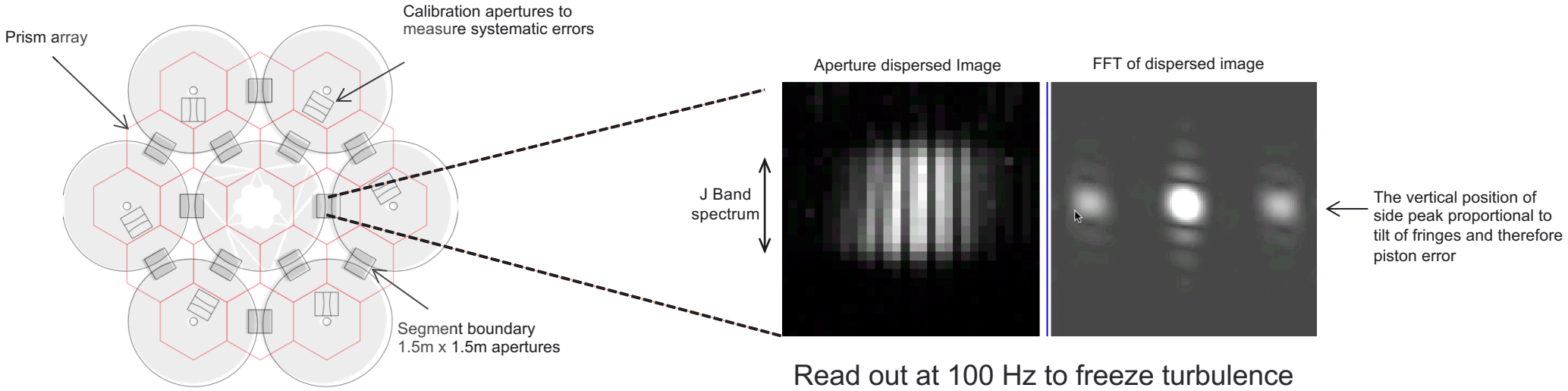
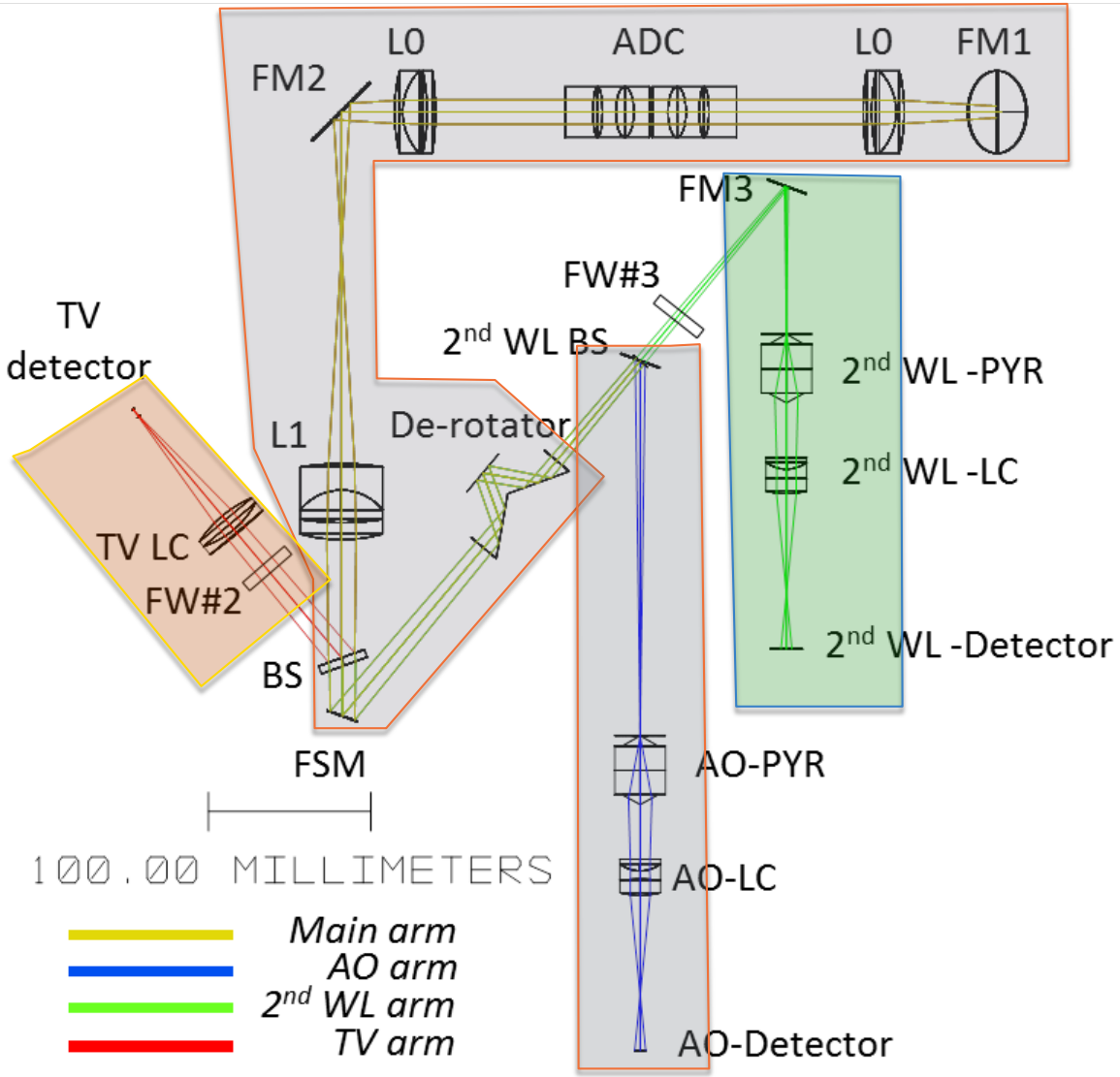
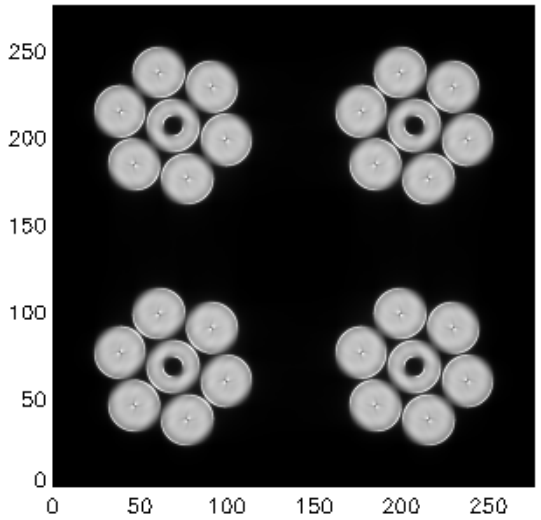


Read out at 100 Hz to freeze turbulence

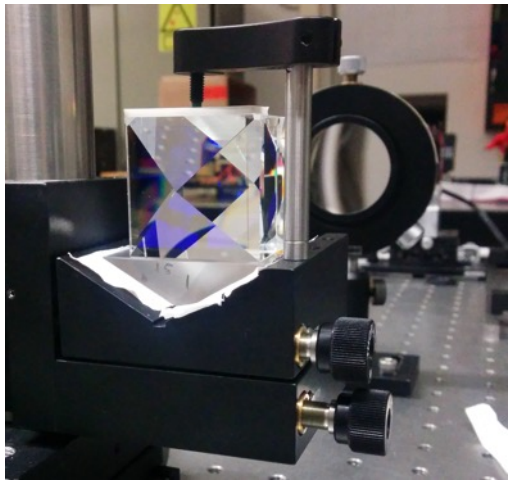
GMT Adaptive Optics Architecture
Natural Guide-star Wavefront Sensing System (NGWS)



Main channel image
(flat wavefront, 10 λ/D modulation)



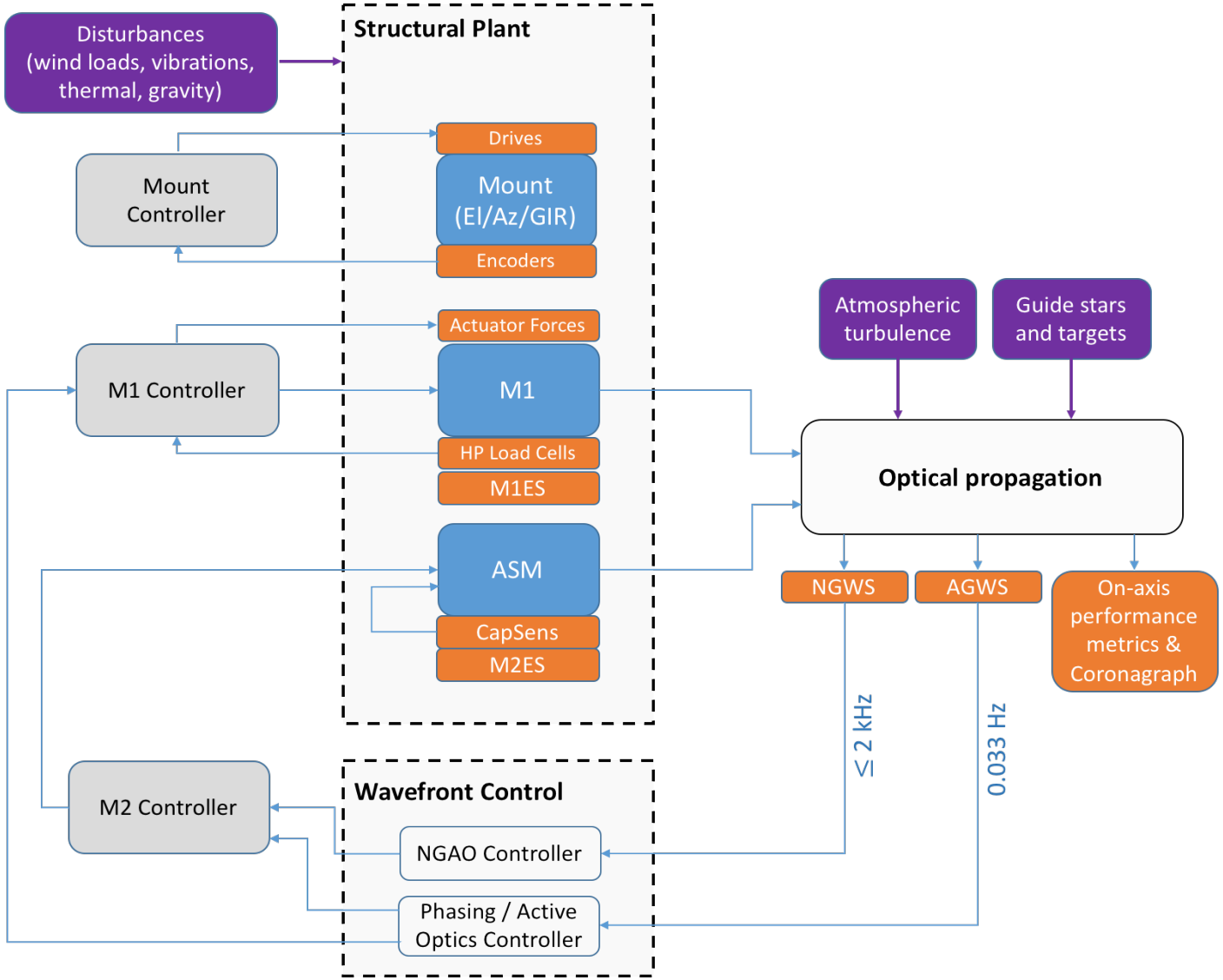
Pyramid optical testing
at INAF-Arcetri



- Designed by INAF-Arcetri (PI: S. Esposito)
- 92×92 pyramid WFS
- 6-element ADC, pupil re-rotator, modulation mirror
- 2 wavelength channels to extend phasing capture range
- Uses two FirstLight OCAM2 cameras

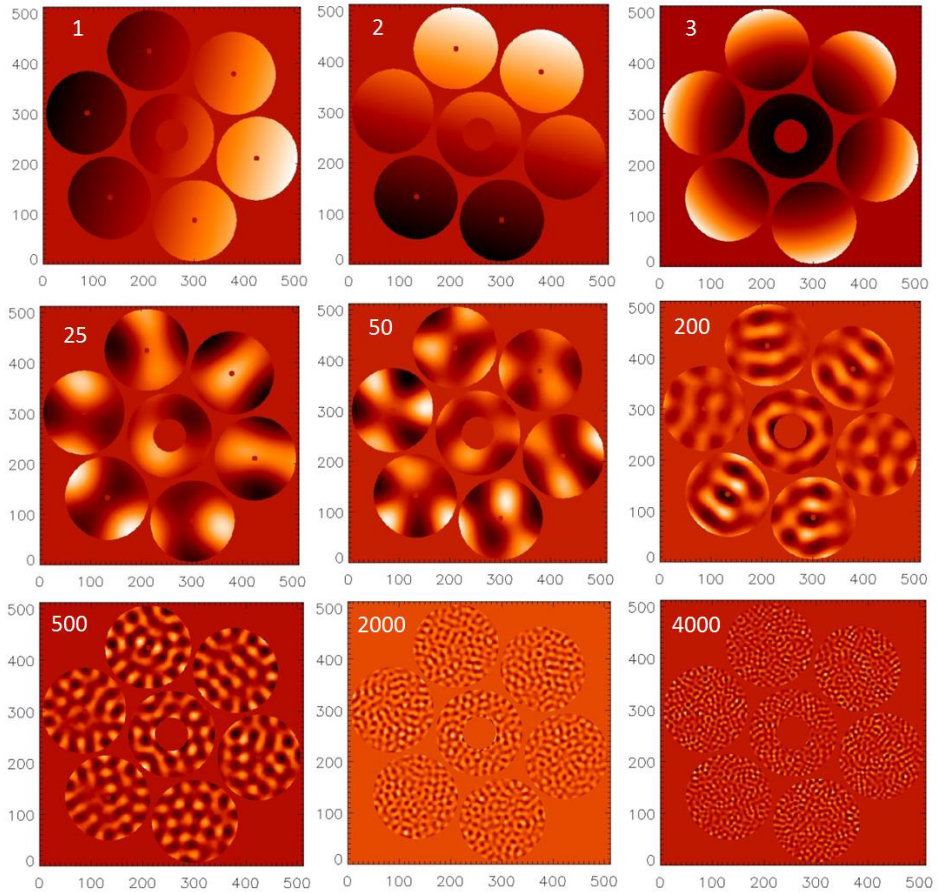
NGAO performance simulations
The GMT Integrated Model

- The GMT integrated model is used to derive requirements, test algorithms, and verify end-to-end telescope performance
- The integrated model includes :
  - Structural performance of mount and optics (using Craig Bampton state space reduction)
  - Models of actuators and drives
  - Fast (GPU) ray-tracing engine for on-axis / off-axis wavefront propagation simulation through atmosphere + telescope.
  - Telescope and WF control loops
- Disturbances (windshake, thermal, vibration, optical turbulence) are modeled independently



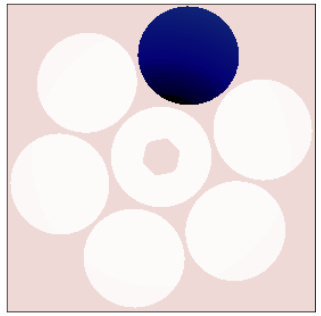
NGAO performance simulations
NGAO modal control basis

Global KL modes
(NGWS PDR 2013)

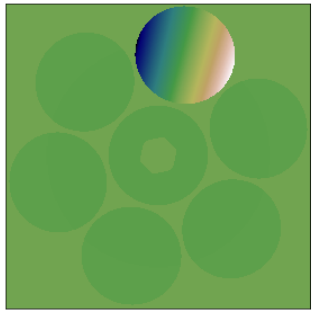


Segment KL modes
(currently being considered)

Seg #1, Mode #1



Seg #1, Mode #2

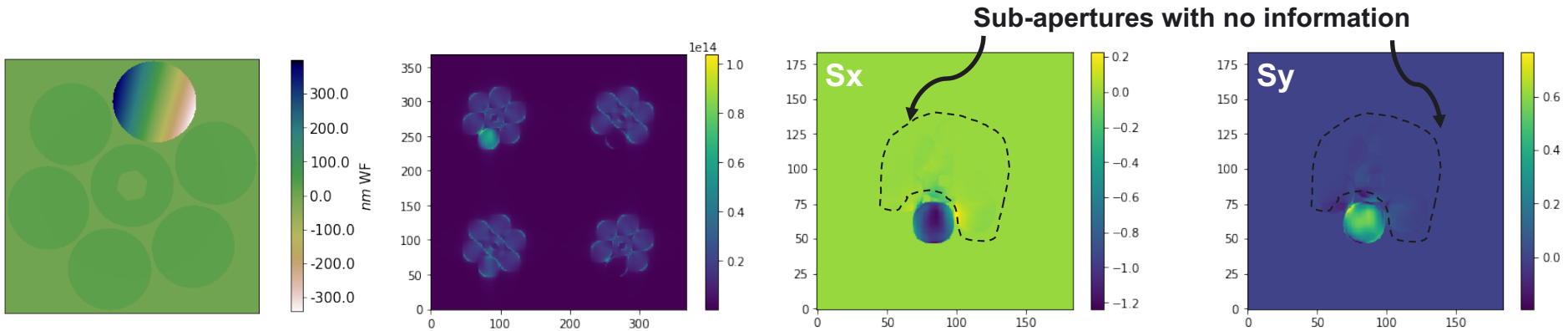


...

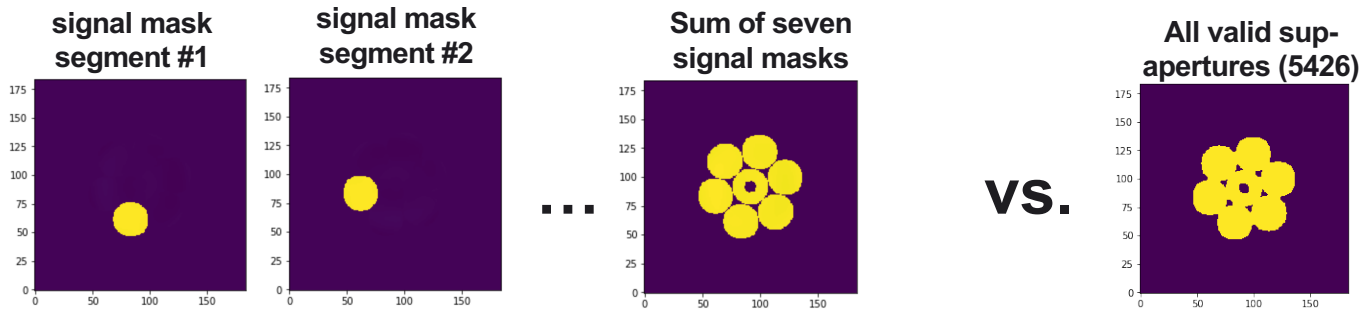
- Provides direct access to segment pistons and segment tilts
- Allows for AO operation with a reduced number of segments
- Allows independent optical calibration of modes

NGAO performance simulations
Signal masking for segment tilt and up

- Signal masks remove sub-apertures of adjacent segments that do not have useful information (just propagate measurement noise):



- Masks for segment KL modes (tip-tilt and up):
  - Note: gaps have been deliberately removed (questionable choice).



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Signal masking for segment piston modes

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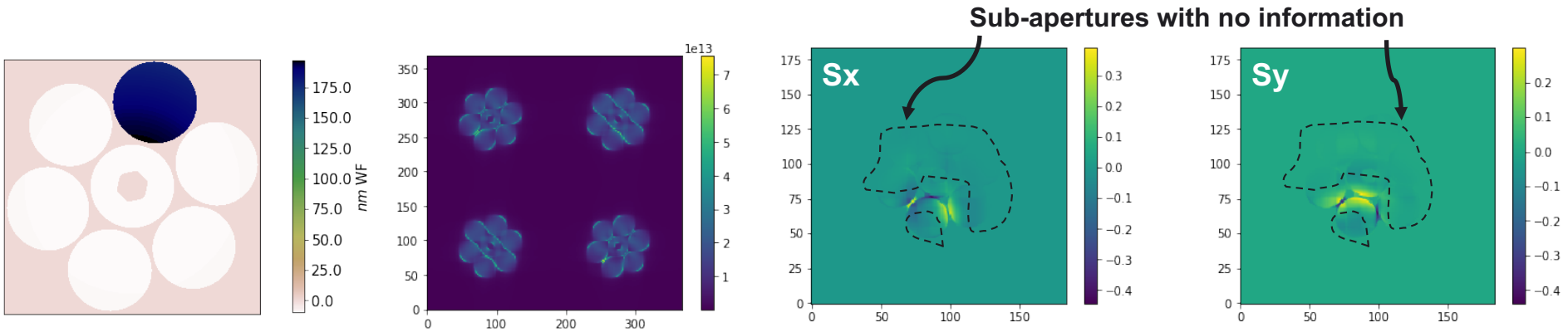
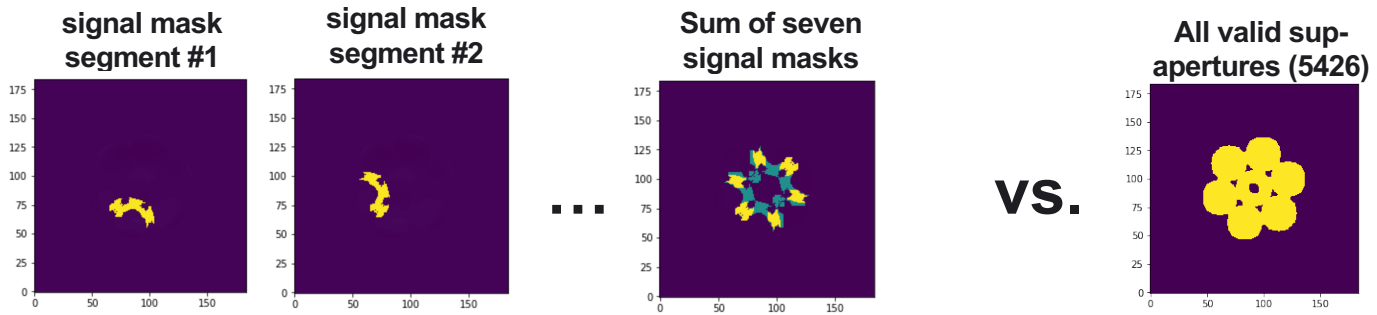


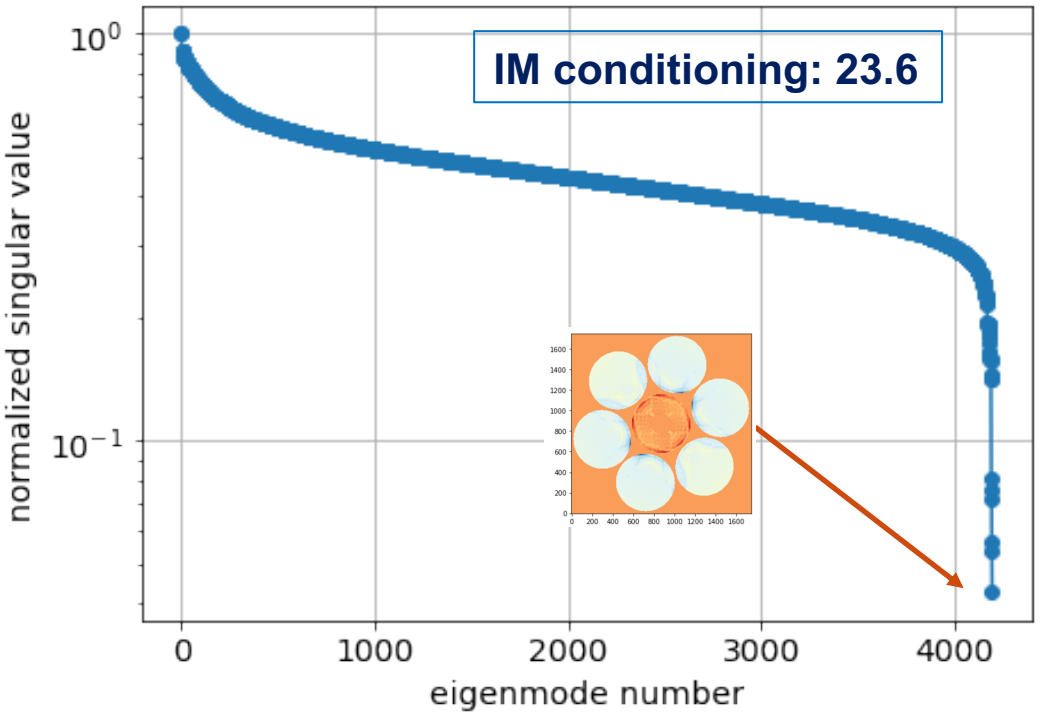
- Masks for segment piston:
  - Note: selected sub-apertures across the gaps and little further.



NGAO performance simulations
Interaction matrix calibration

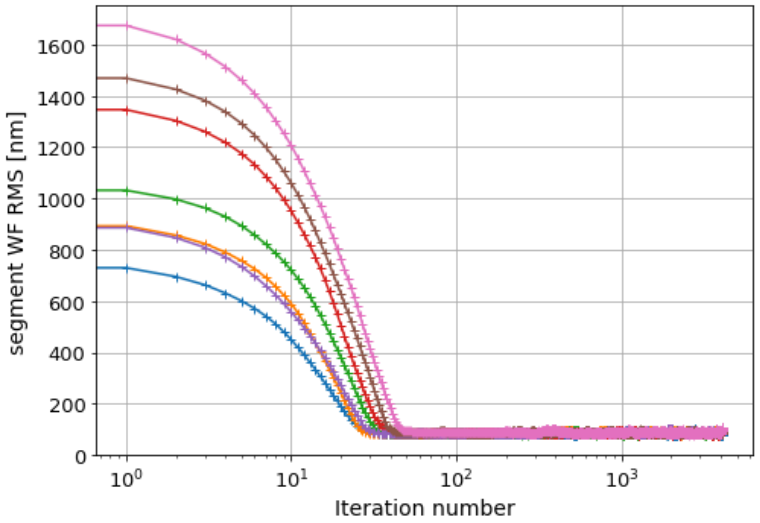
- Interaction matrix between ASM and pyramid WFS:
  - ASM control modes: 600 KL modes per segment
  - Pyramid WFS:
    - modulation of $\pm 2\ \lambda/D$ (circle sampled with 24 points)
    - Signal masks applied accordingly to interaction matrix.
    - Segment piston of central segment NOT controlled (i.e. acts as the reference for differential piston of outer segments).

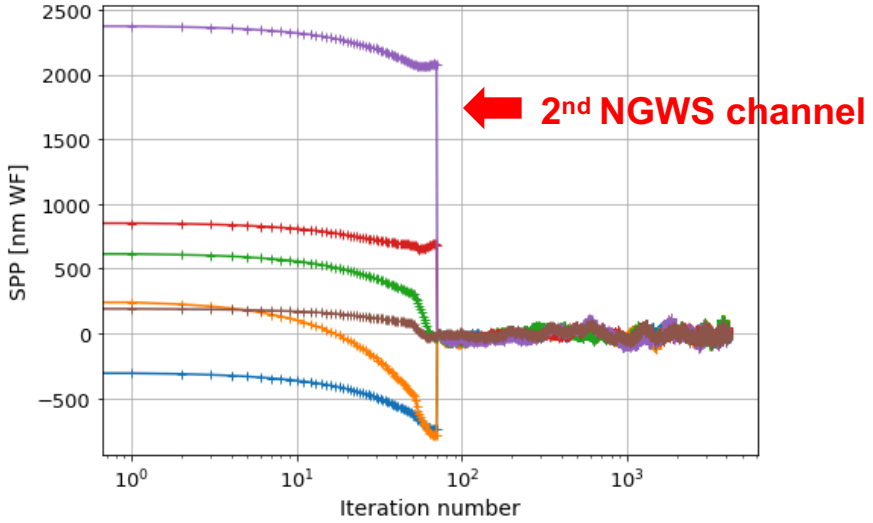
SVD of Interaction Matrix

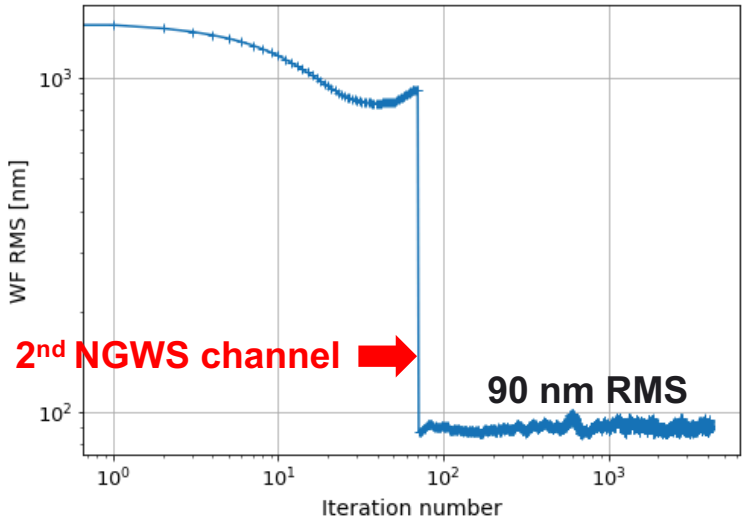


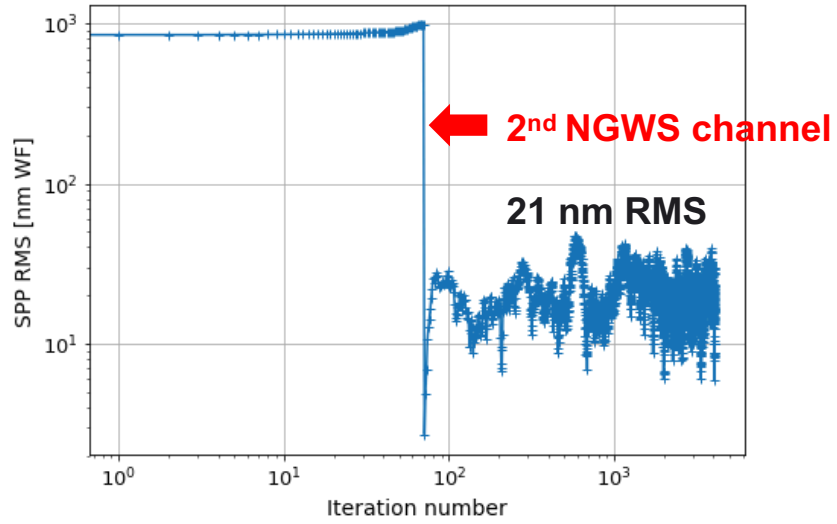
NGAO performance simulations
Median turbulence conditions (0.63” seeing)

- **NGAO system**
  - Adaptive Secondary Mirror:
    - 600 KL modes / segment
  - Pyramid WFS:
    - 92 x 92 sub-apertures
    - Modulation: $\pm 2\lambda/D$
    - GS mag(R) = 10
    - EMCCD: RON 1 e- RMS; $\sqrt{2}$ excess noise.
  - Temporal controller:
    - Sampling rate: 1kHz
    - Total time delay: 2 frames
    - Simple integrator: g=0.5
- **Atmospheric turbulence**
  - 7 layers median profile
    - r_0 = 15 cm @ 30º zenith angle.
    - τ_0= 3.5 ms; L_0= 25 m.





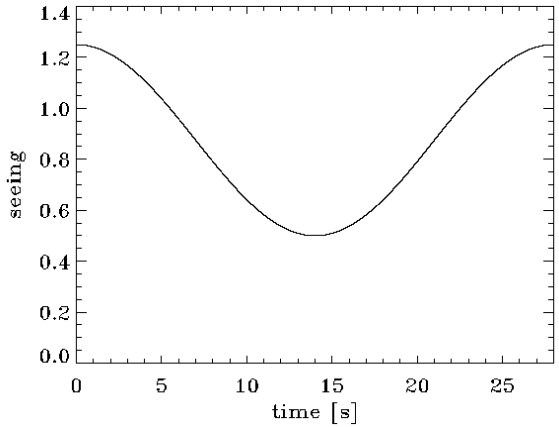


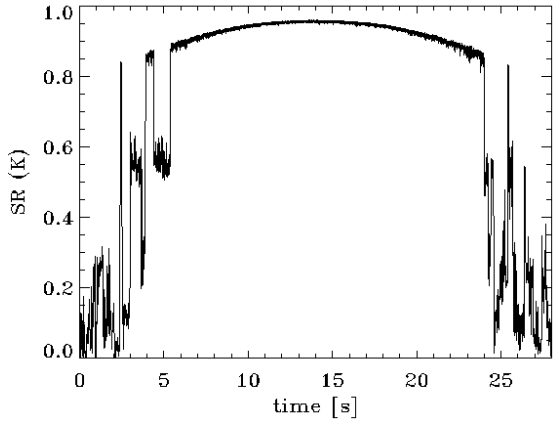


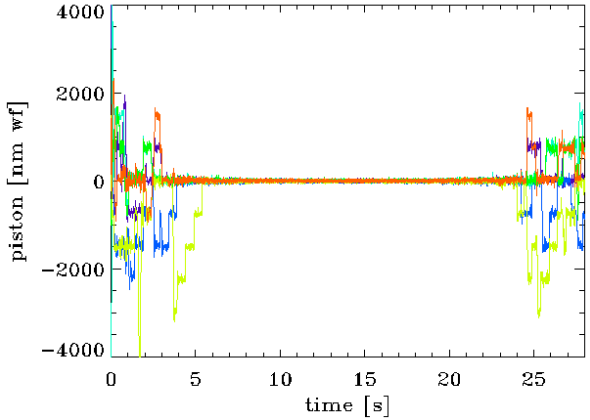
NGAO performance simulations
Performance vs. seeing

- Segment piston “ejections” occur when seeing conditions degrade (NGWS PDR 2013 results):

- WFS in R+I band
- Well optimized modal IIR controller

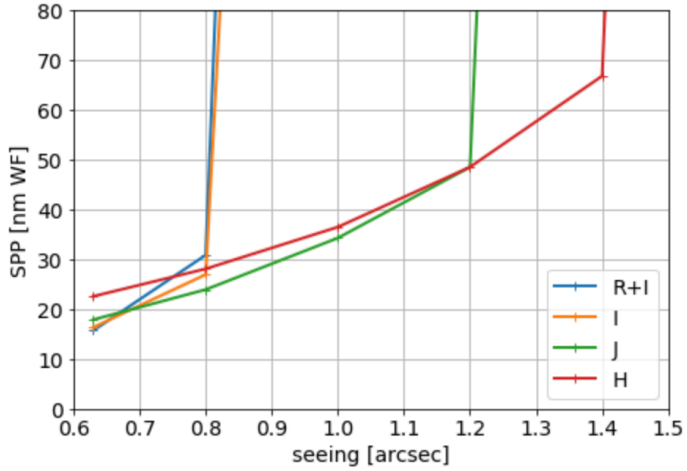






- Alternative options to improve segment piston rejection currently under evaluation:

- WFS at different wavelengths
- Simple integrator controller

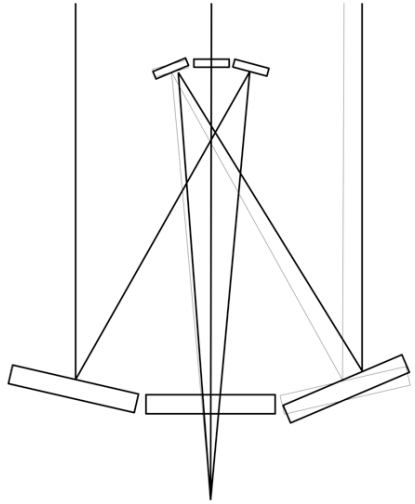


NGAO performance simulations
Adaptive Optics / Active Optics / Phasing interactions

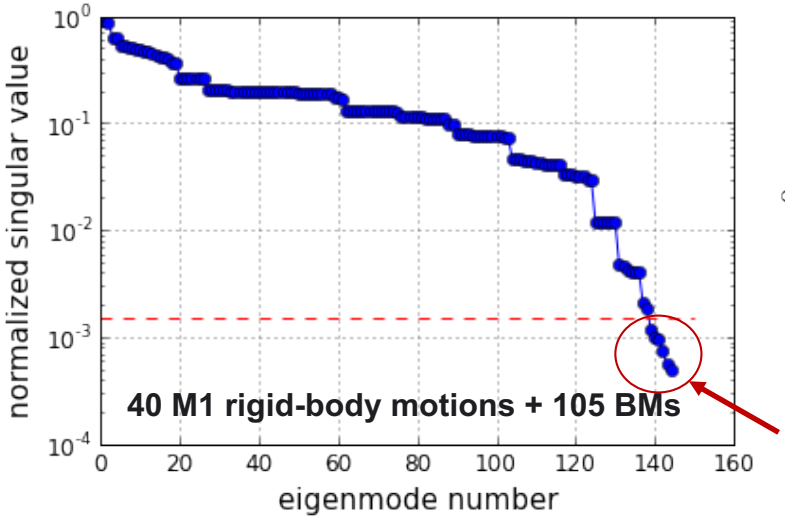
- M1 active optics / phasing residuals will be be compensated by the ASM.
  - OK for on-axis performance but degrades performance in the field of view.
- Active Optics / Phasing control strategy in AO mode:
  - Combines the AGWS SH & DFS measurements into a single reconstructor.
  - Modes calibrated are:
    1. M1 segment rigid-body motions;
    2. Up to 27 M1 bending modes per segment;
  - All modes calibrated with AO loop closed.

$$R_M = M_M^{\dagger} = \begin{bmatrix} \left(\frac{1}{G_{DFS}}\right) M_{DFS} \\ \left(\frac{1}{G_{SHS}}\right) M_{SHS} \end{bmatrix}^{\dagger}$$

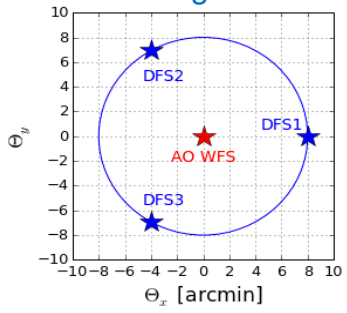
M_{DFS}: AGWS DFS Interaction matrix
M_{SHS}: AGWS SH Interaction matrix
G_{DFS}: norm of M_{DFS} matrix
G_{SHS}: norm of M_{SHS} matrix



M1 segment tilt, corrected by M2 segment tilt, leads to zero tilt in the focal plane but *field-dependent segment phase piston error.*

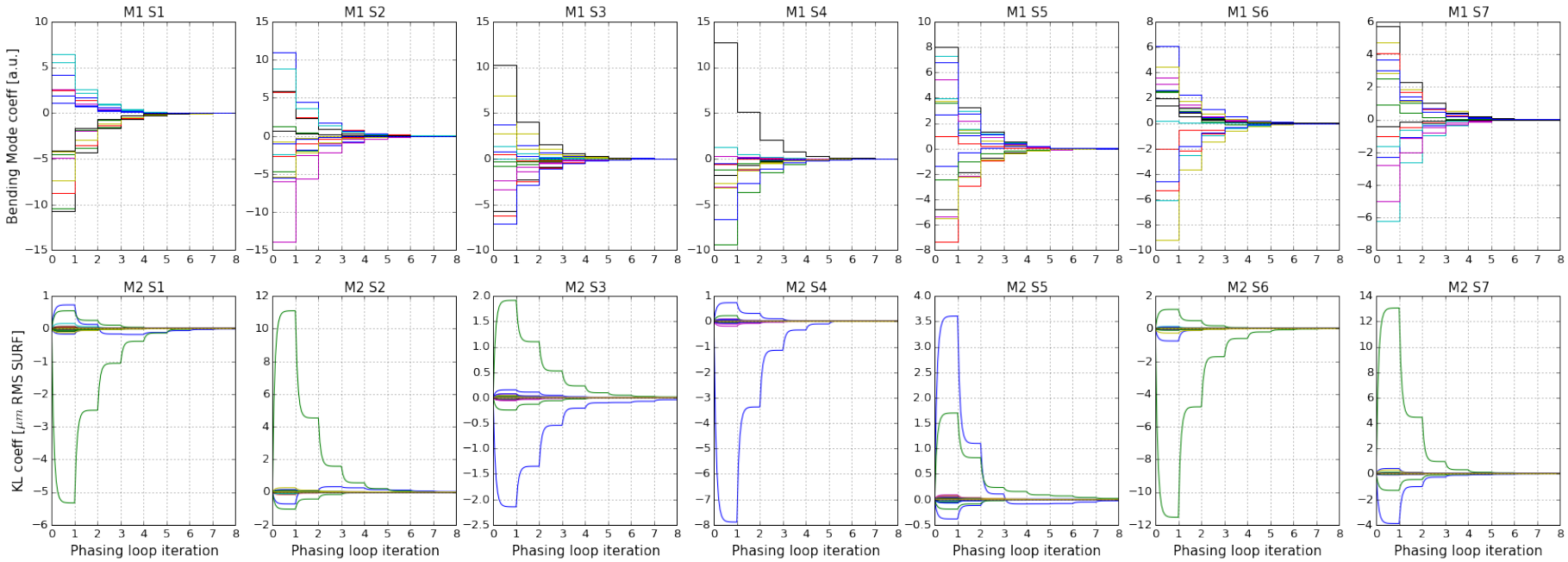


3 AGWS guide stars



NGAO performance simulations
Adaptive Optics / Active Optics / Phasing interactions

- M1 Active Optics residuals: M1 rigid body motions + 5 μm RMS of M1 figure errors
- Note: no atmospheric turbulence simulated.

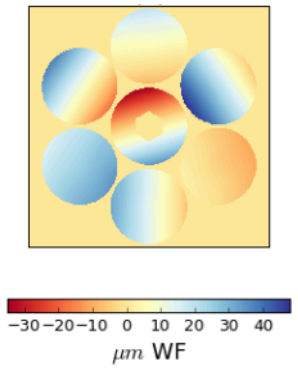


All M1 figure errors (bending modes) converge to zero

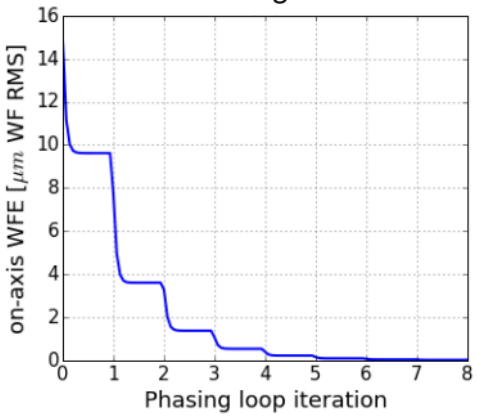
NGAO performance simulations
Adaptive Optics / Active Optics / Phasing interactions

- M1 Active Optics residuals: M1 rigid body motions + 5 μm RMS of M1 figure errors
- Note: no atmospheric turbulence simulated.

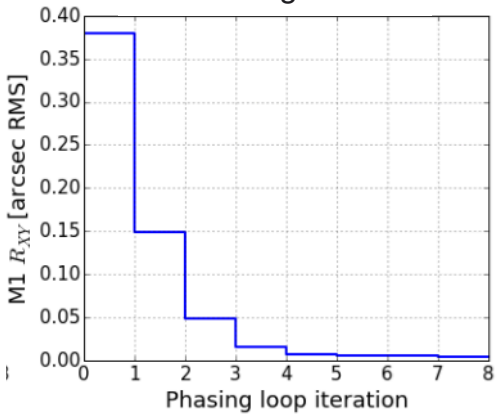
M1 Initial scramble



On-axis WFE convergence



M1 segment tilts convergence



Field-dependent segment piston errors are removed.

Conclusions and Future Work

- Conclusions:
  - Stable operation of NGAO loop in 95% seeing conditions (< 1.1 arcsec seeing).
  - Convergence of AO / Active Optics / Phasing loops demonstrated with high-fidelity simulations
- Future work:
  - Evaluating alternative 2nd NGWS channel designs.
  - Performance evaluation including telescope dynamics and wind buffeting disturbances.
  - Evaluating large NCPA compensation with the NGWS.