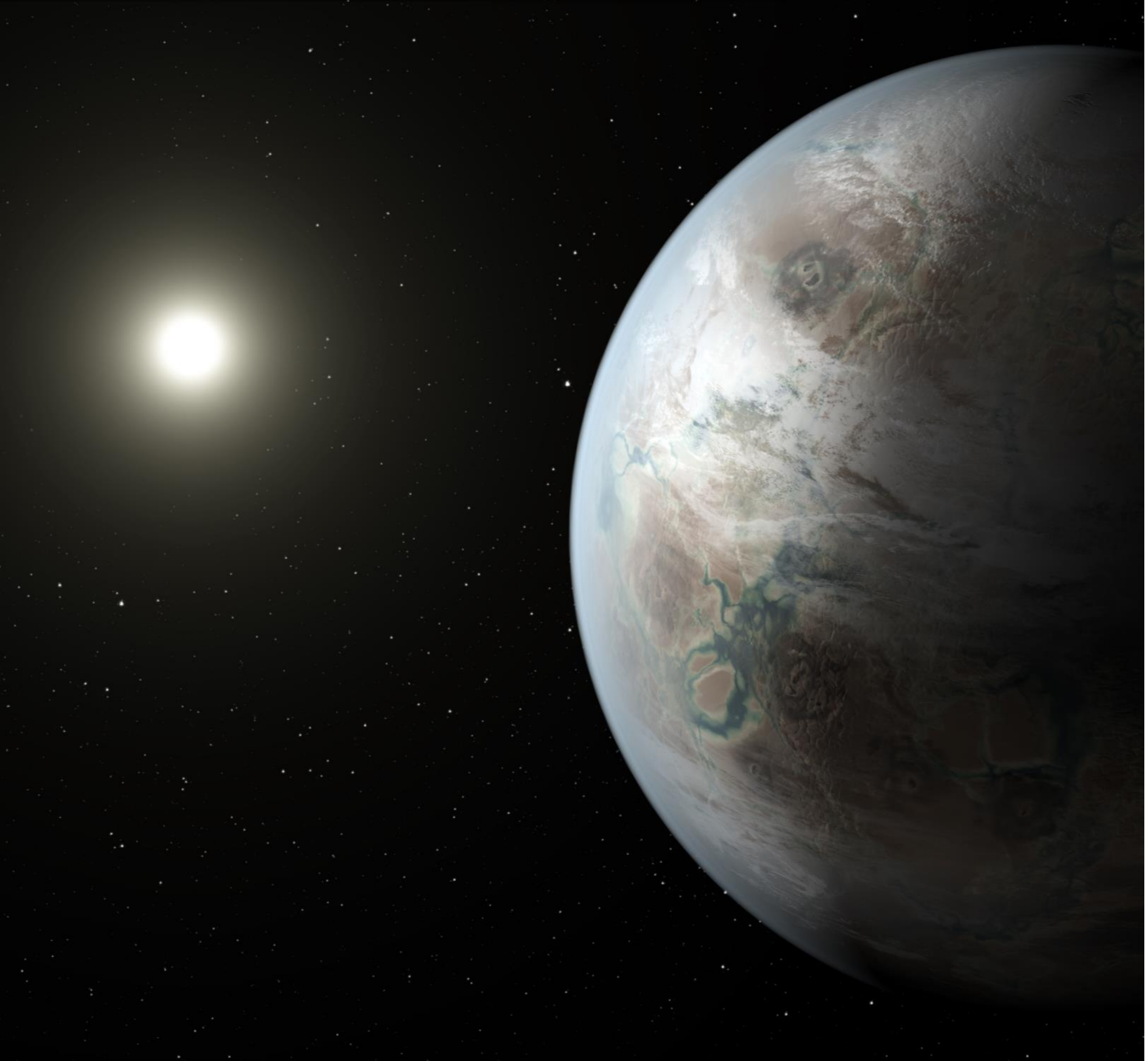


More details in Potier et al. 2022a (SPIE) and Potier et al. 2022b (JATIS)

ExEP Technology Colloquium Series

Wavefront control for coronagraphs on Segmented Space Telescopes in steady state

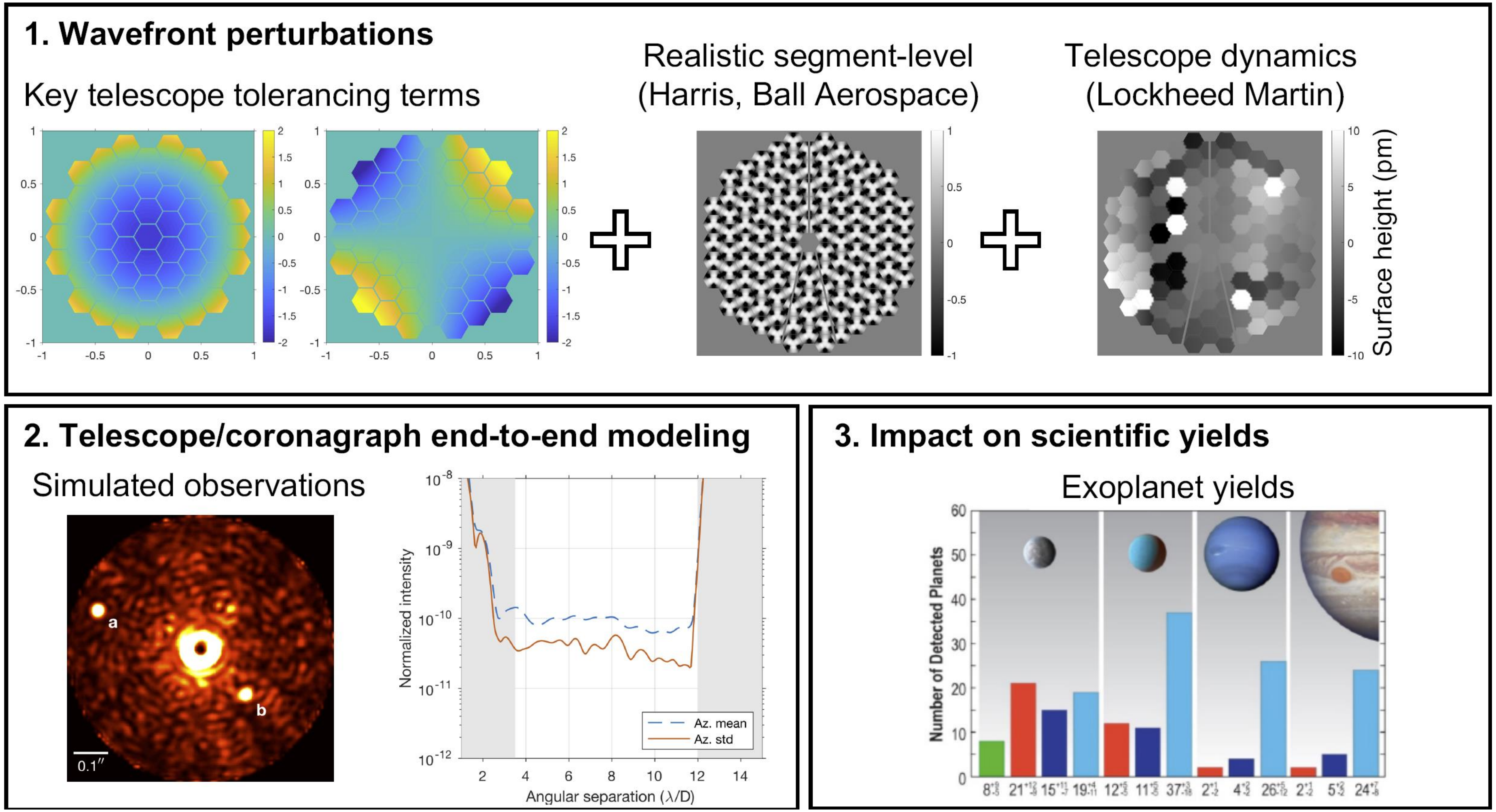
October 27th, 2022

Axel Potier, SCDA team

Jet Propulsion Laboratory
California Institute of Technology

Stability tolerance for direct imaging of Earth-like planets

Segmented Coronagraph Design and Analysis workflow overview:



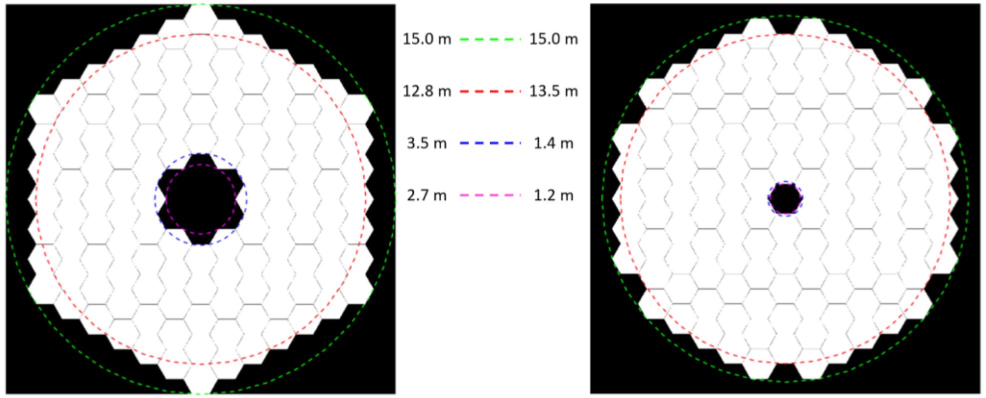
This panel is notional, simulation pending.

SCDA study objectives and finding

Phase 1: Proof for static solution

Main findings:

- Various coronagraph designs **can achieve better than 10^{-10} contrast** with a static segmented telescope aperture, so long as the segment gaps are below 0.1% of aperture diameter
- Design optimization by **reducing central obscuration** and maximized in-circled diameter



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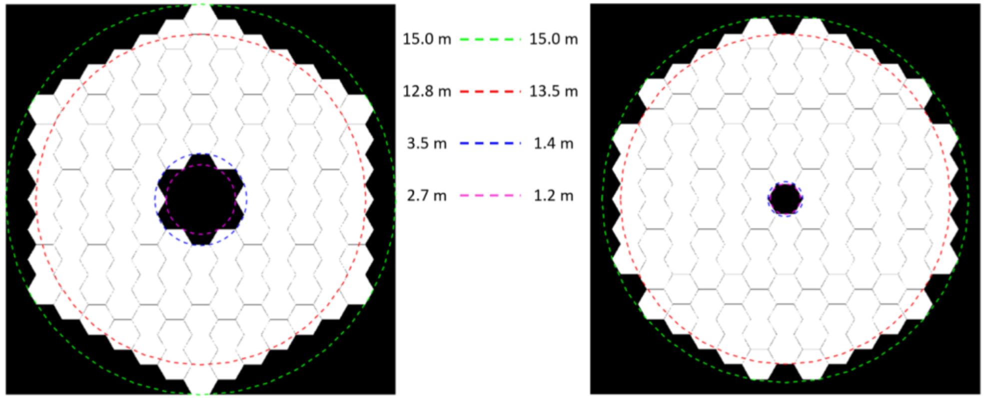
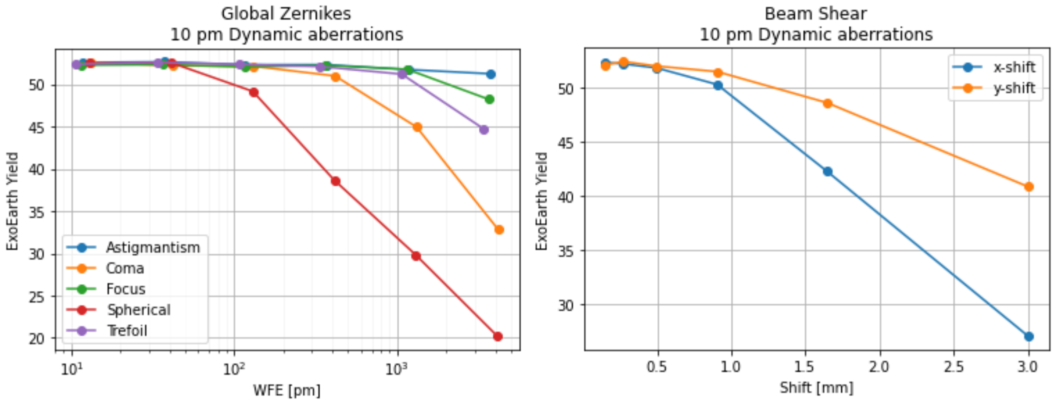


Phase 2: Sensitivity of science yield to telescope stability

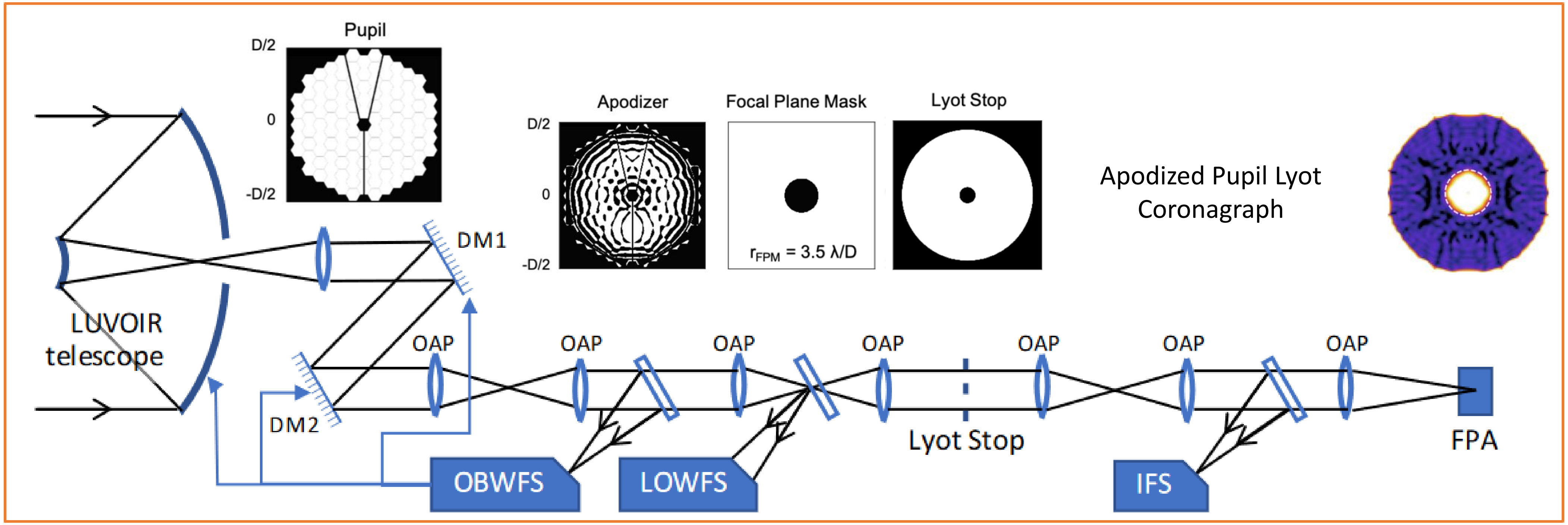
Main findings:

- **Yield is robust** against most modes of slow telescope aberrations.
- **Exception: beam shear**. Misalignment needs to remain below 0.001% of the pupil diameter
- Factor contributing to robustness: coronagraph designs optimized for robustness against aberrations + Yield calculator's target list and observing strategy is adaptive per coronagraph performance.



Credits: Roser Juanola-Parramon/ Dan Sirbu

Phase 3: Potential benefits of instrument wavefront sensing and control



LUVOIR Final Report 2019

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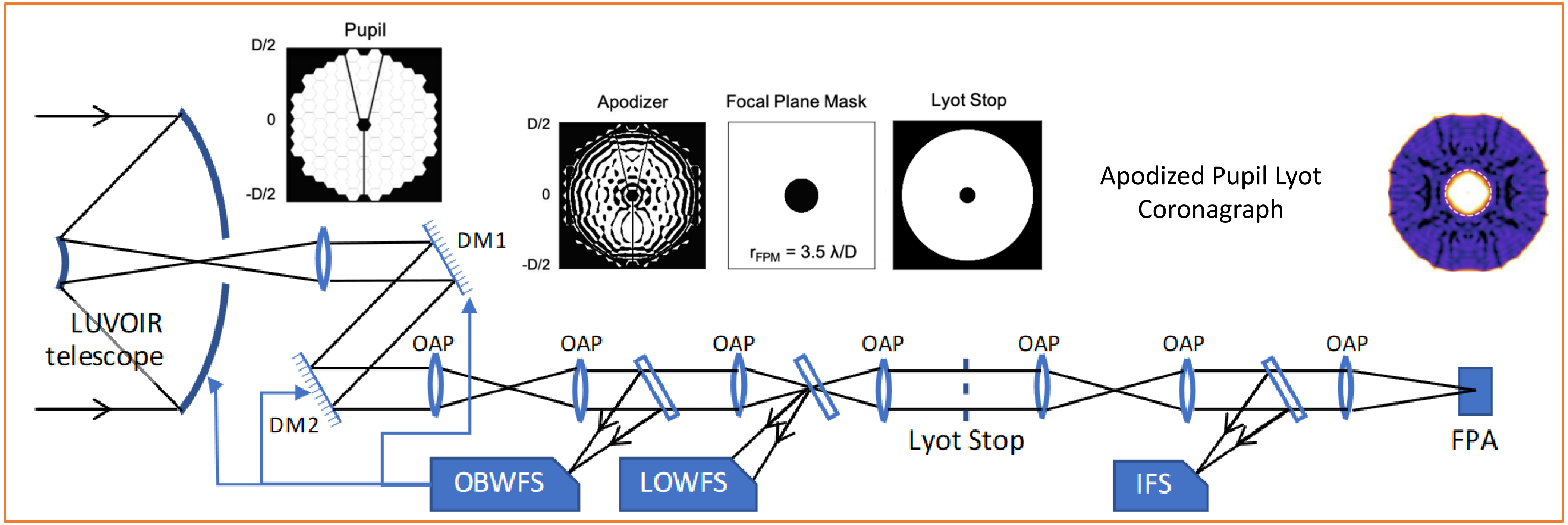
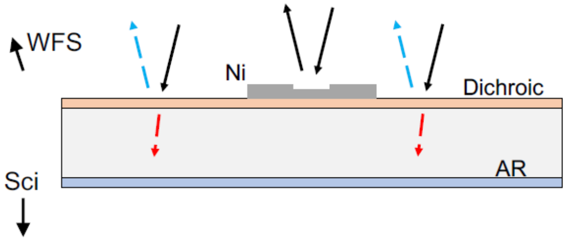


LUVOIR Final Report 2019

Zernike Wavefront Sensor encoded in the Focal Plane Mask

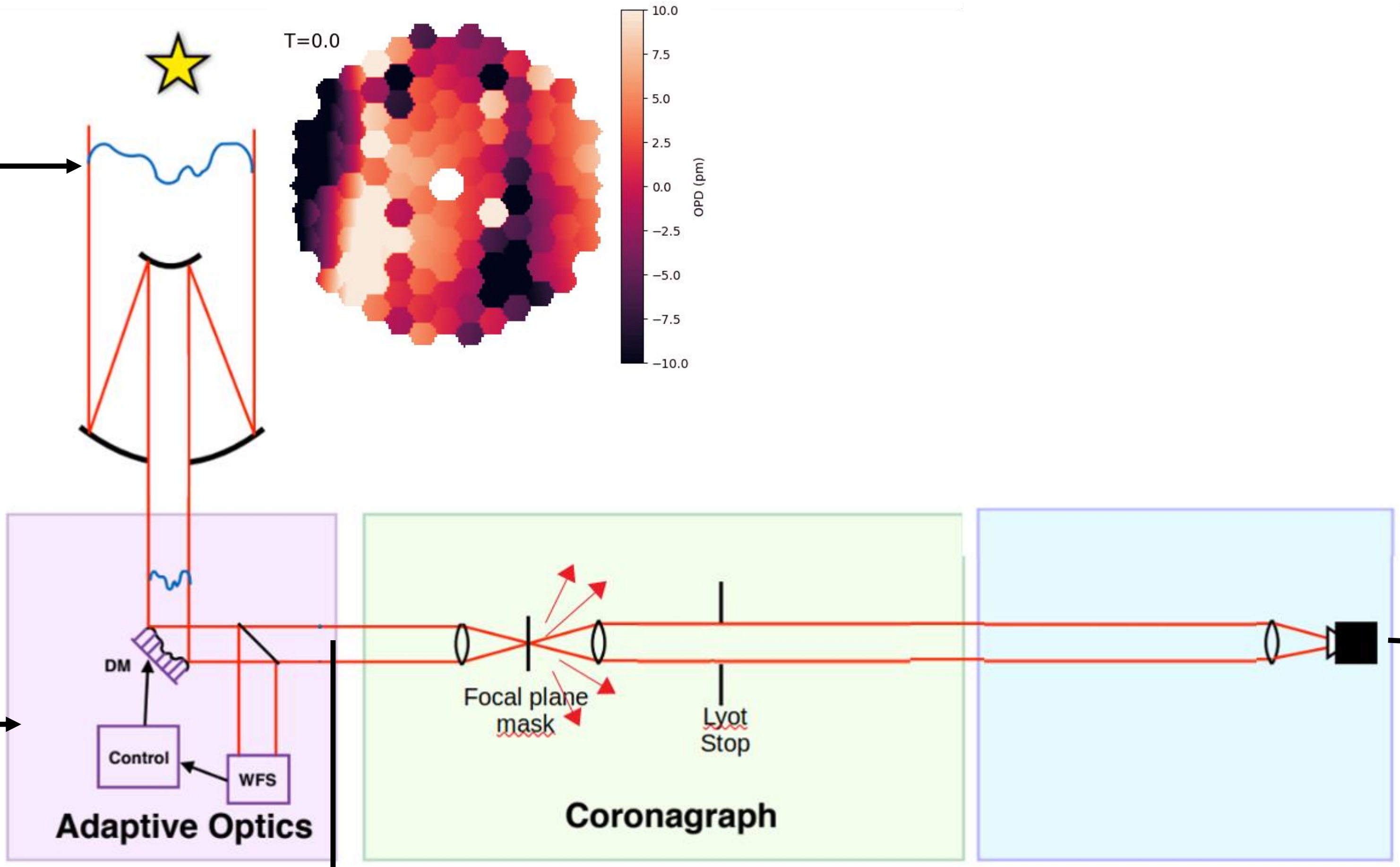


Common path/ Simultaneous/ High resolution/ High Sensitivity

Assessing LUVOIR-ECLIPS performance with WS&C: Workflow overview

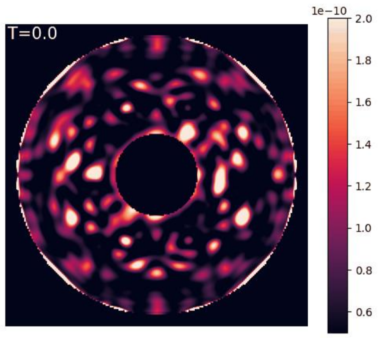
1) LMC times series (realistic dynamic aberrations)

2) LUVOIR telescope and AO loop assumptions



3) Minimize Wavefront Residual

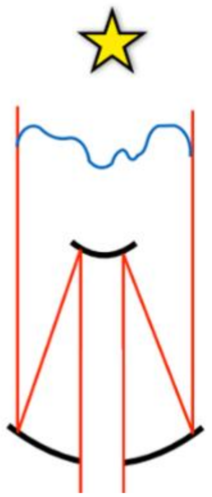
Courtesy of David Doelman



4) Contrast performance

5) Yield performance

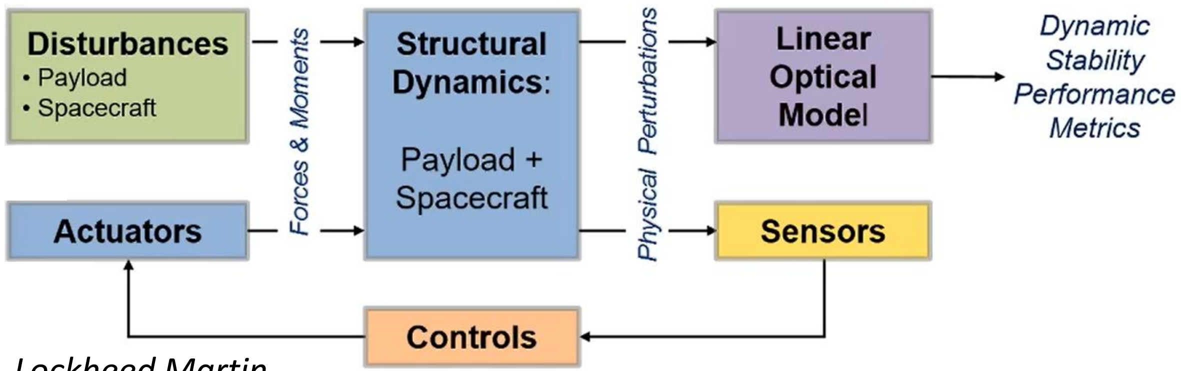
1) Spatiotemporal analysis of realistic optical perturbation



a) Integrated modeling of a large segmented telescope structure

LMC developed an integrated modeling tool with dynamics, optical model and controls model. It takes into account:

- **Disturbances** from the multi-stage pointing control system, assuming Lockheed disturbance free payload.
- **Finite element model of the OTA** with primary mirror segments and subsequent optics relative to each other
- A **linear optical model** to probe the optical degradation



Lockheed Martin

The model does not take into account any metrology system

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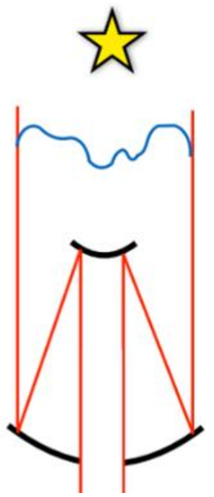

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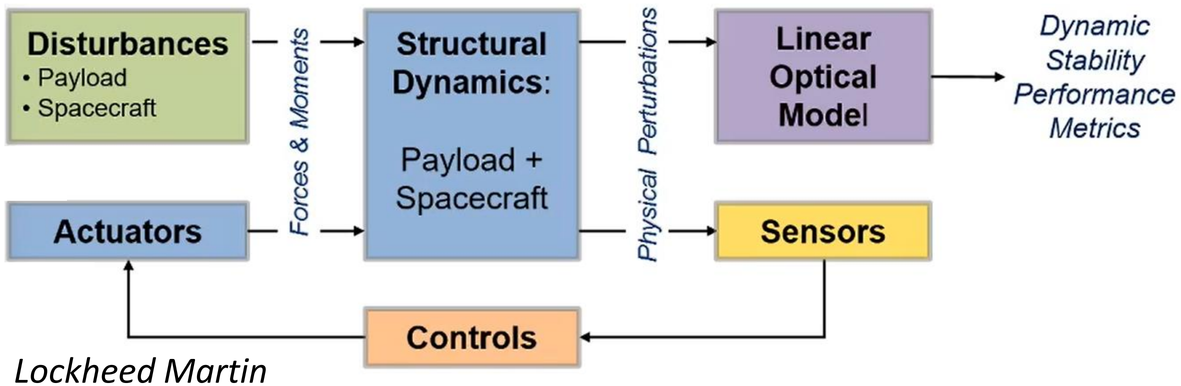


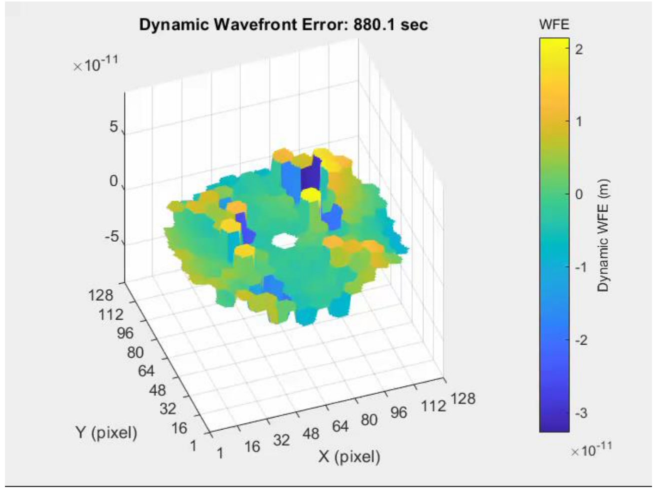
Lockheed Martin

The model does not take into account any metrology system

The level of disturbance remains unknown. **Three different levels of perturbations were considered per architecture**, playing with cable stiffness, voice coil actuator force noise and uniform structural damping.

Substantial relaxation of the hypotheses for LUVOIR B to reach same level of perturbation rms than LUVOIR A

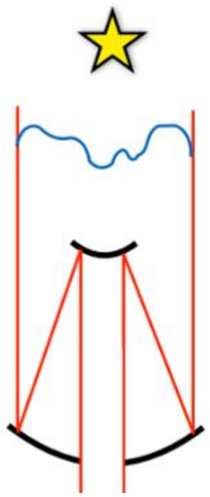
The output LOS is low enough to be considered negligible.



LUVOIR A 3pm rms: A. Chopra, L. Dewell, A. Nordt, K. Tajdaran

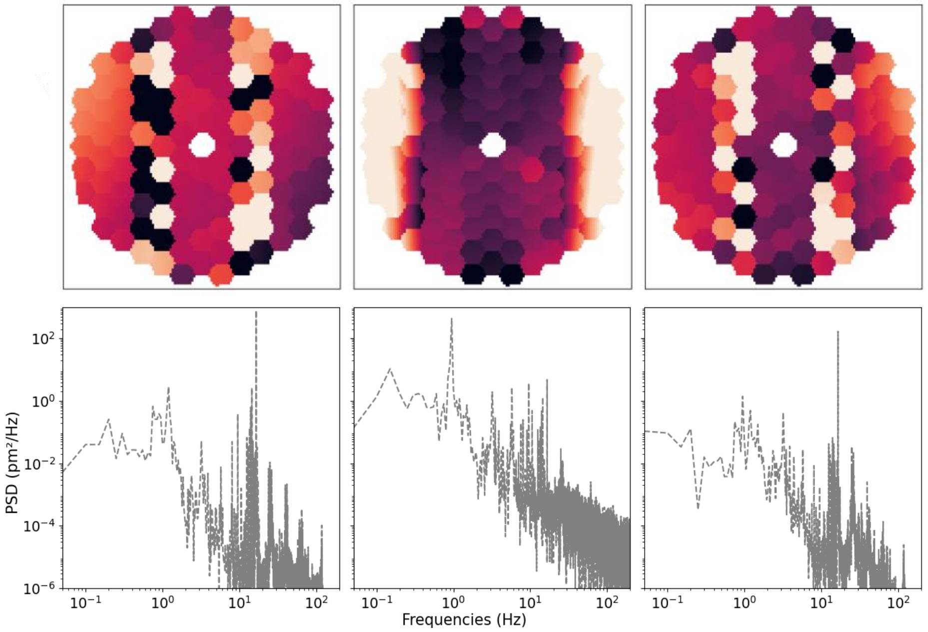
1) Spatiotemporal analysis of the perturbation

b) Modal decomposition of the time series



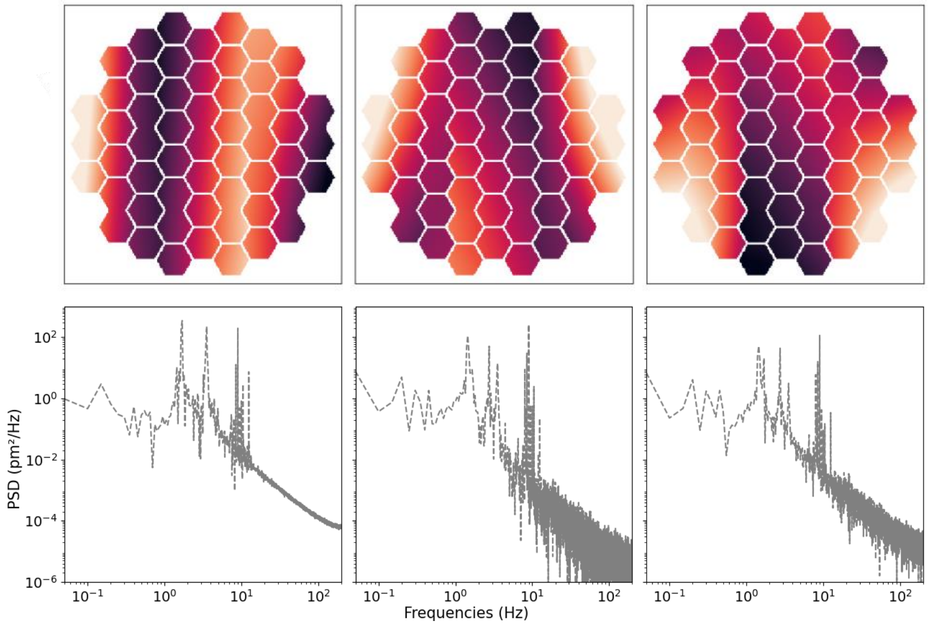
Principal component analysis (PCA):

LUVOIR - A



- Mid to High spatial frequencies
- 76% of the total variance
- Single vibrations at 16.5 Hz or 0.9Hz

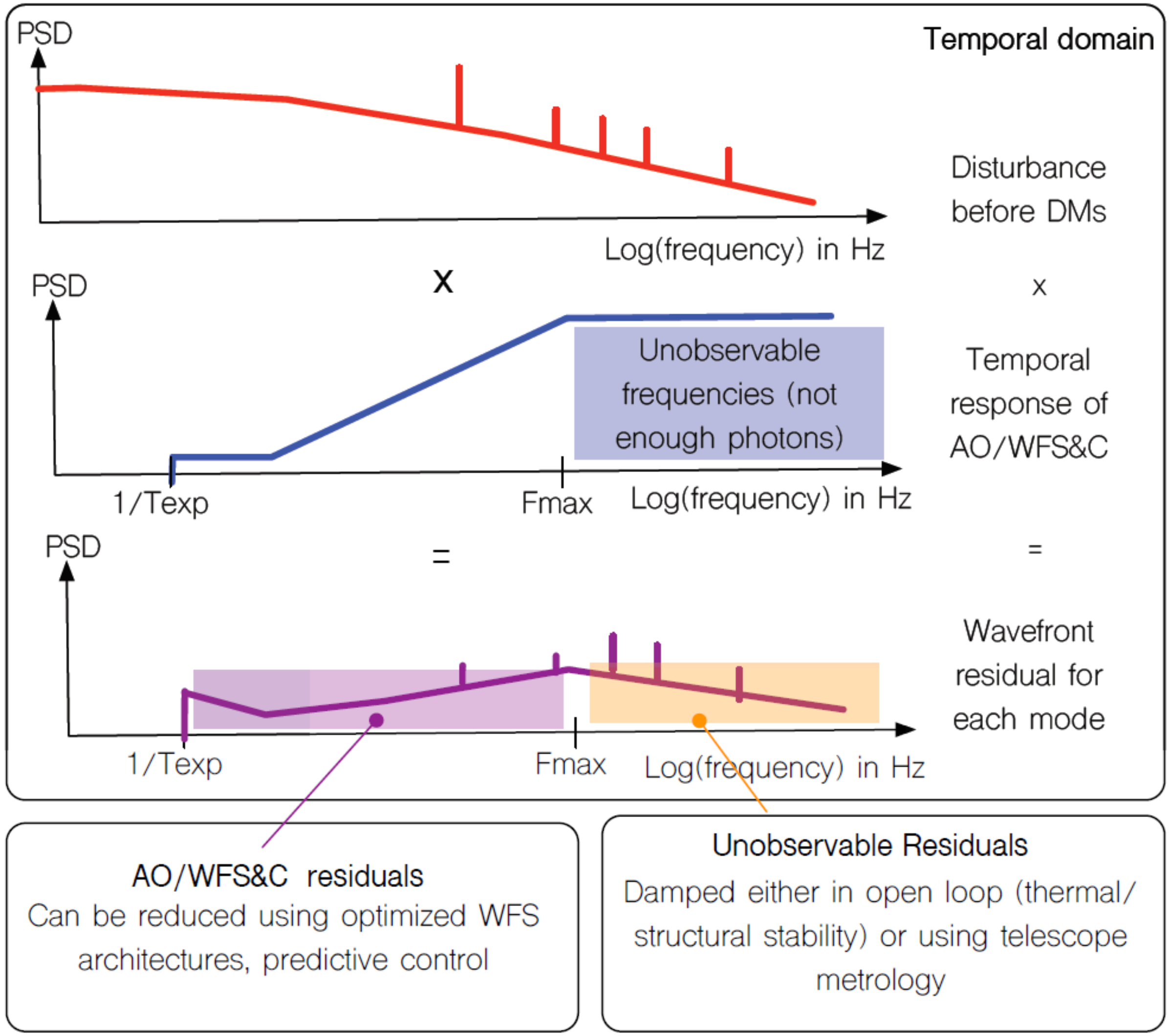
LUVOIR - B



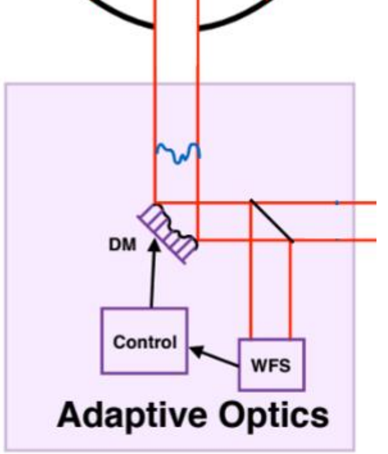
- Lower spatial frequencies
- 98% of the total variance
- Multiple vibrations per mode

2) WS&C analytical modeling

a) Filtering the low temporal frequencies for each mode in parallel

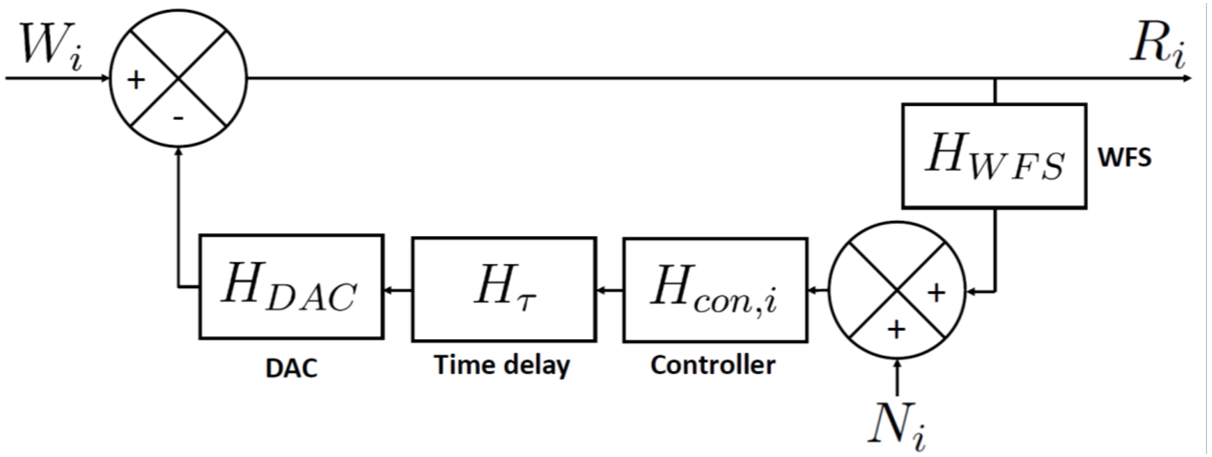


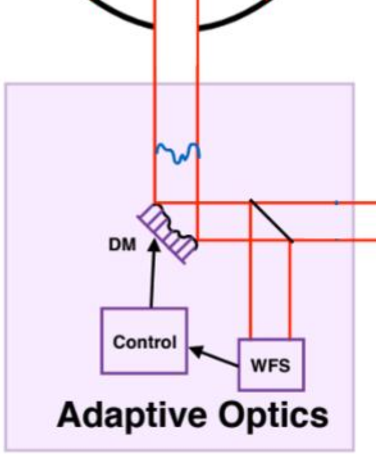
Pueyo et al. 2018



2) WS&C analytical modeling

b) Temporal modeling with transfer function: Rejection





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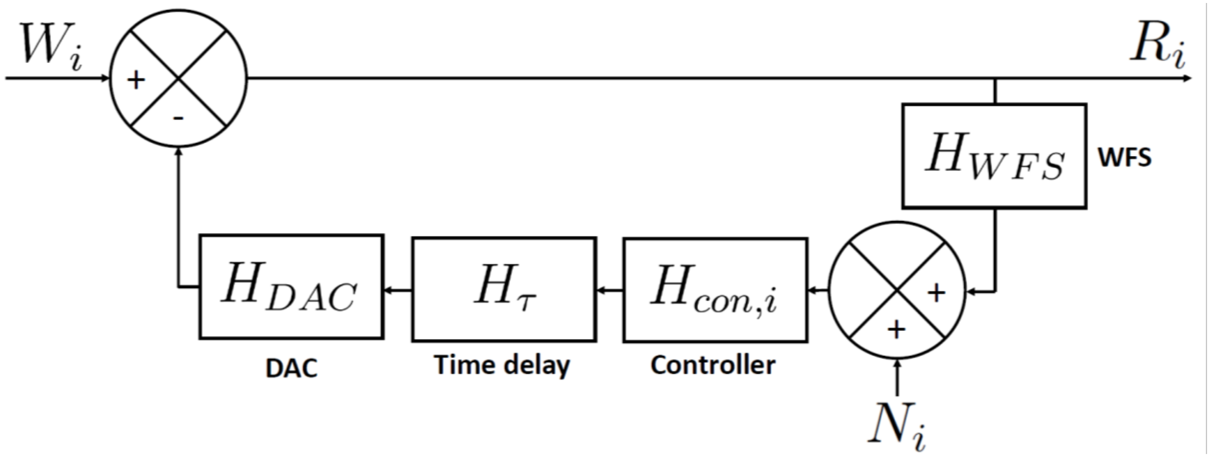
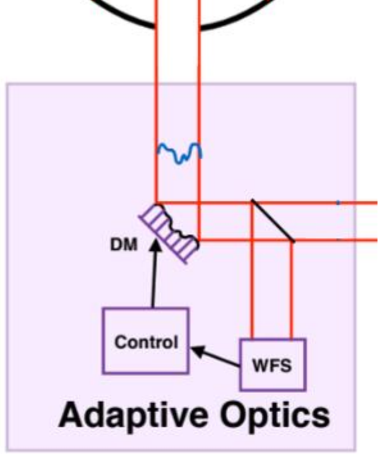
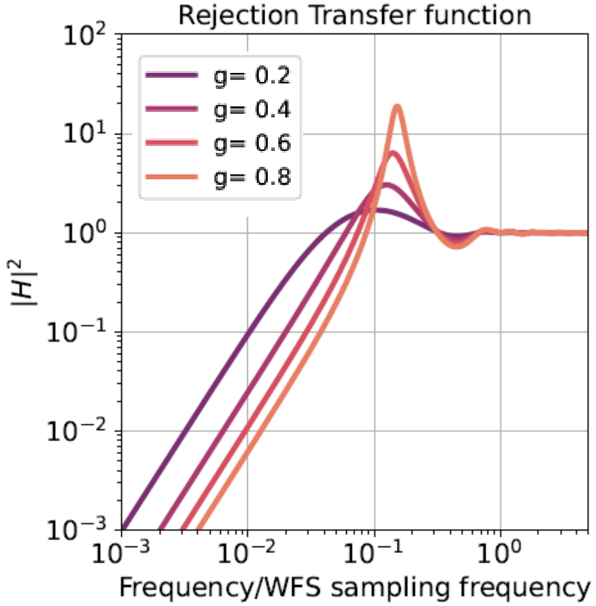




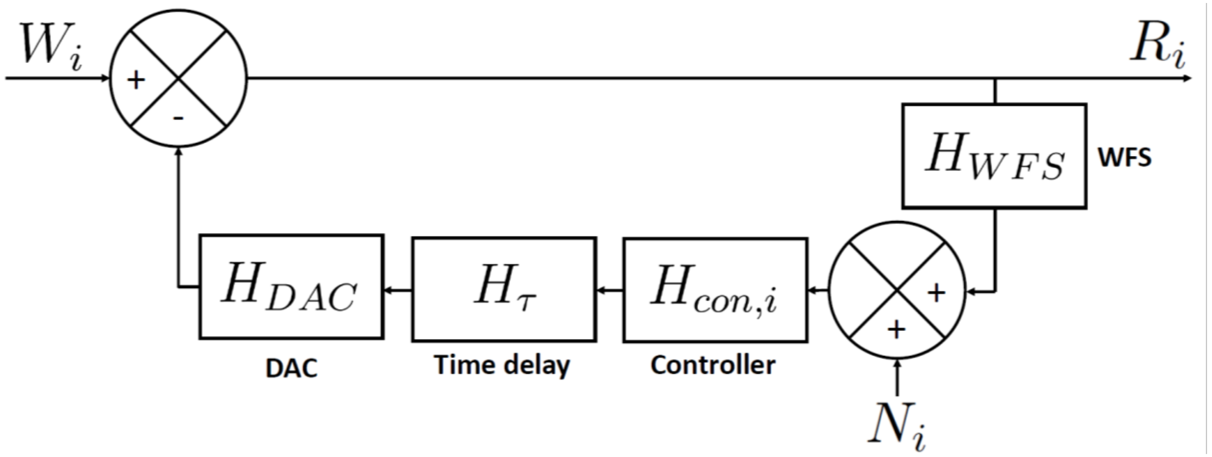


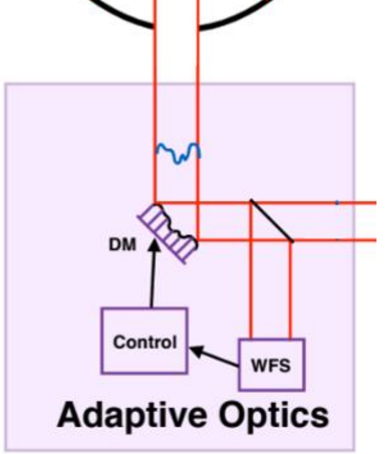
The temporal bandwidth is ~1/10 of the servo-loop frequency.
The rejection transfer function depends on the **loop frequency**, the **servo lag** and the **controller gain**

→ **The gain is optimized** for each mode to enhance rejection

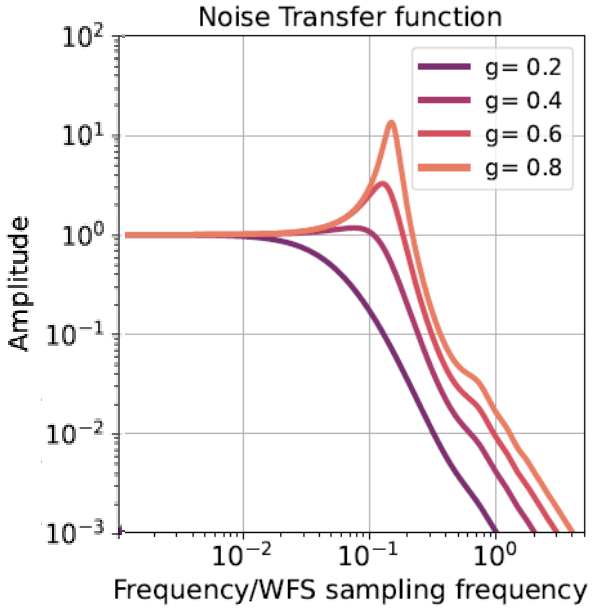
2) WS&C analytical modeling

b) Temporal modeling with transfer function: Noise introduced by the WFS

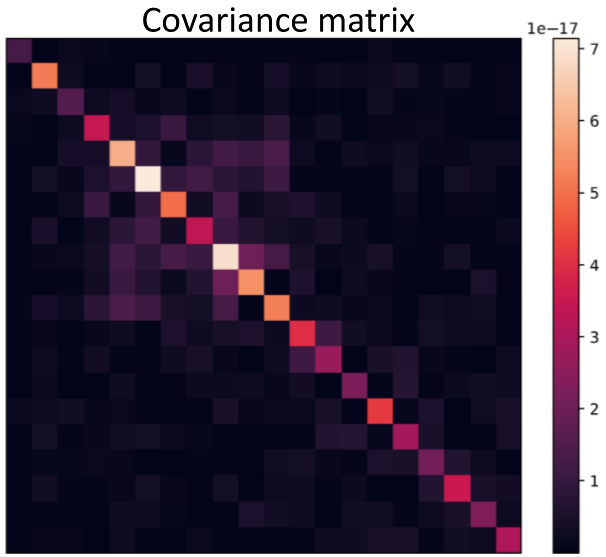




PSD_N =



×

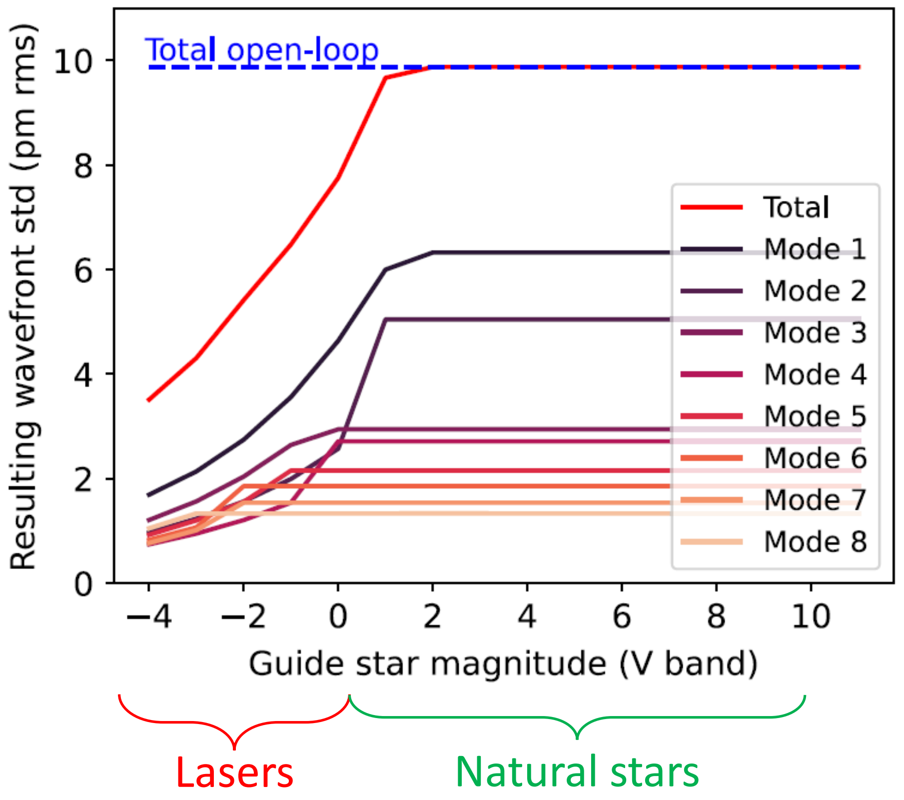


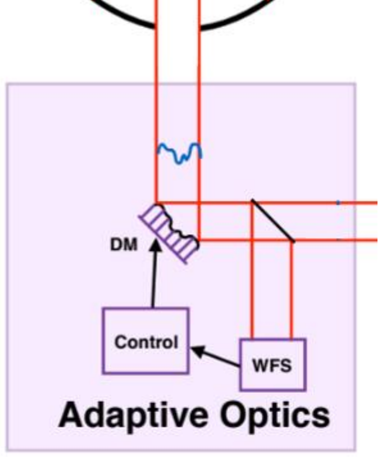
× **$(SNR)^{-2}$**

Depends on: **gain, loop frequency** | **Spatial modes, nb pixels across the beam** | **Stellar magnitude, loop frequency**

3) Minimizing wavefront residuals: LUVOIR A – 10pm rms

a) Optimized integrator (Gendron et al. 1995)





The AO system is useful if Mv<1. It would require a laser!

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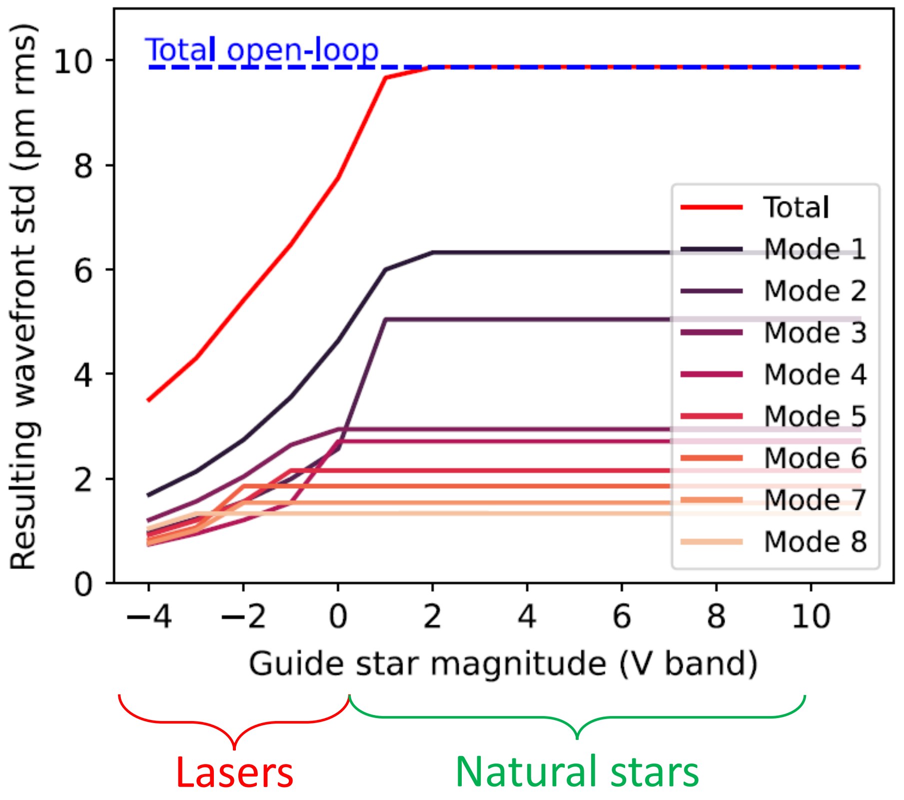

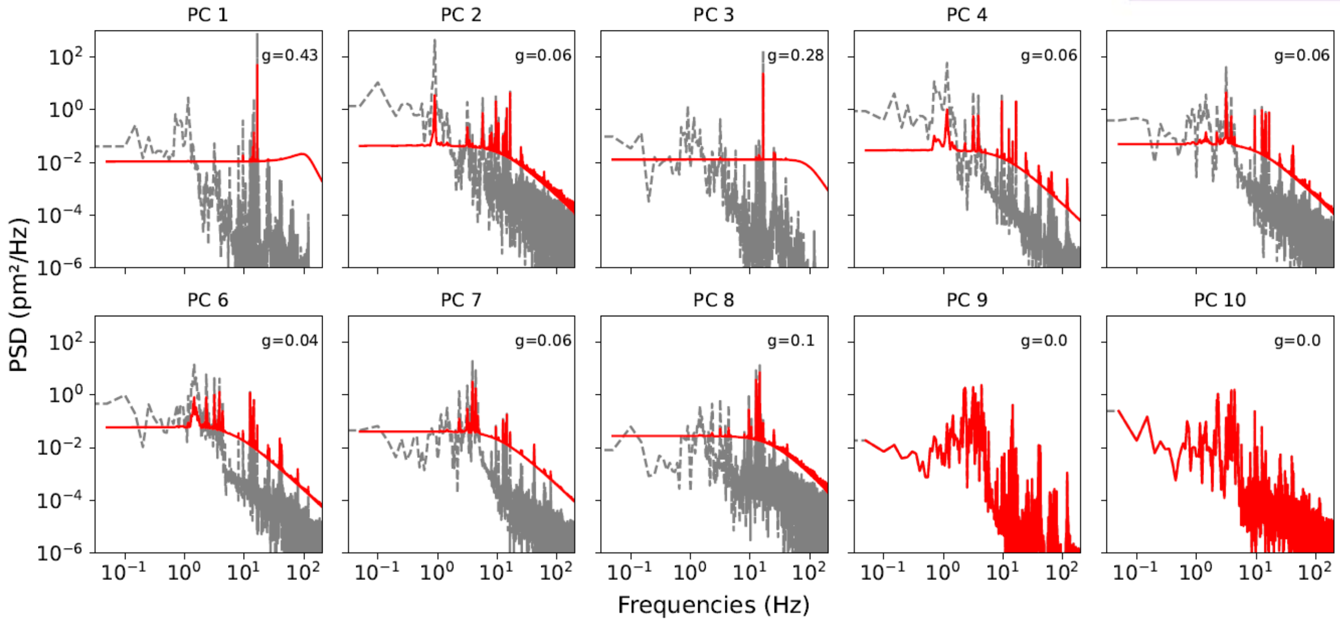

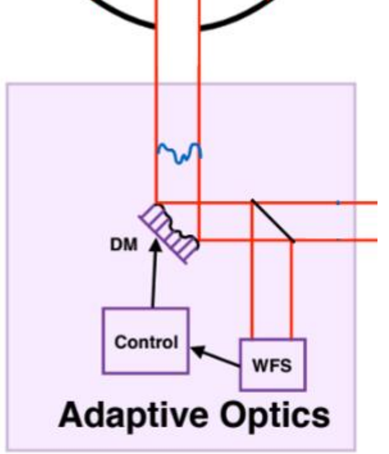

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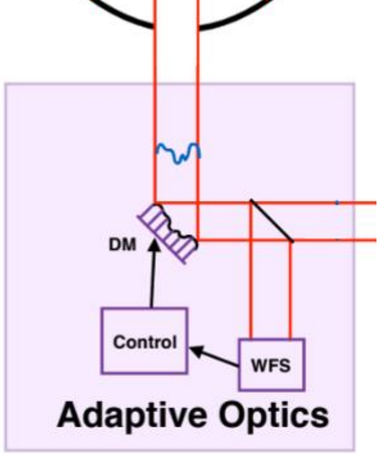
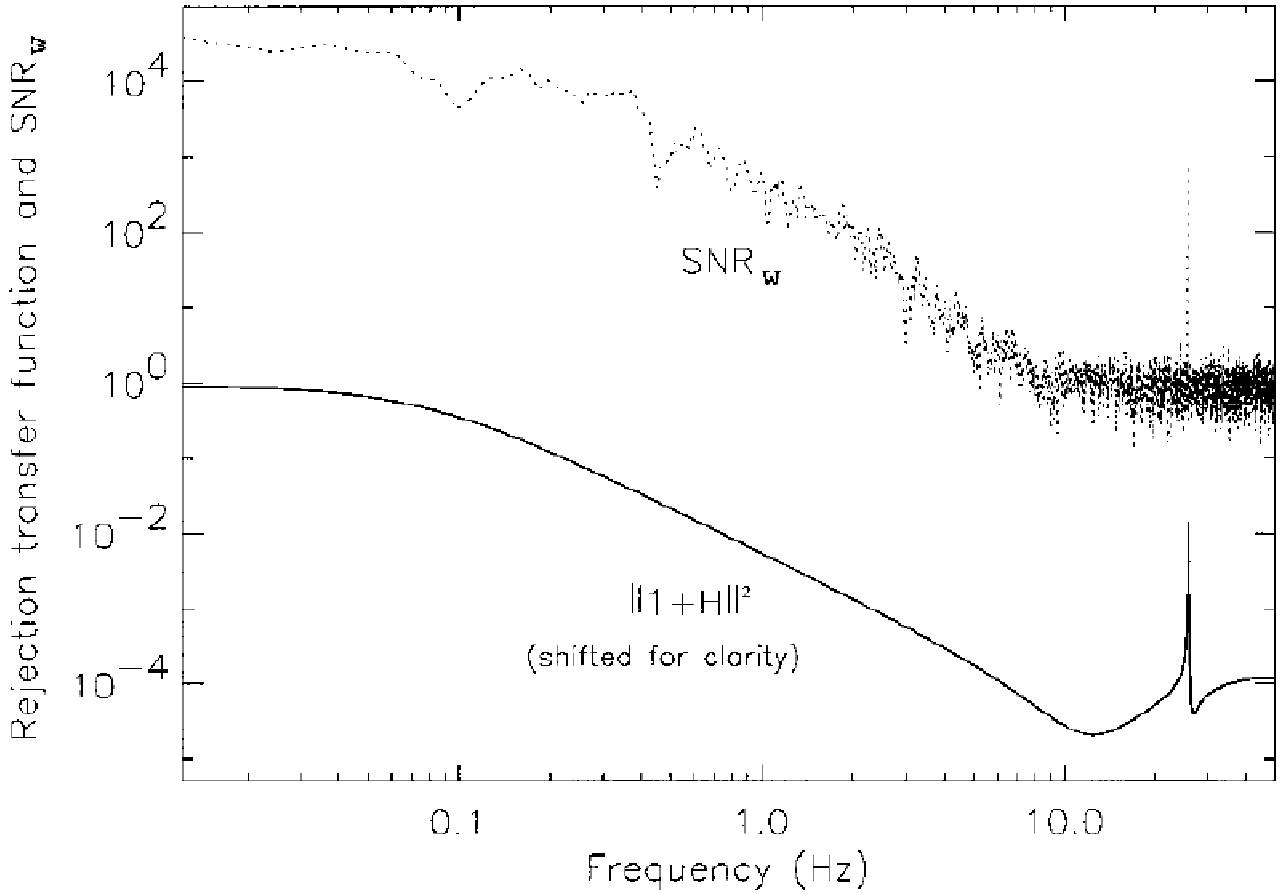


Using previous wavefront measurements, and knowing perfectly the dynamics of the aberrations, we can **shape the control response to minimize vibrations**.

General controller TF:

$$\mathscr{C}(z) = \frac{\sum_{i=0,q-1} a_i z^{-i}}{1 + \sum_{i=1,p-1} b_i z^{-i}}$$



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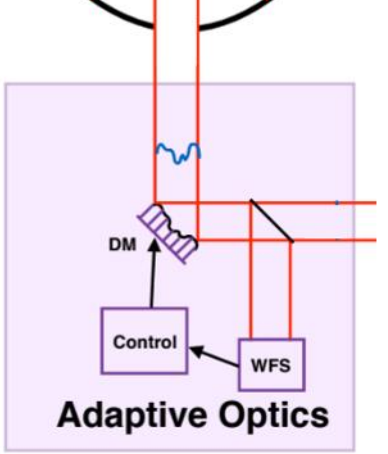
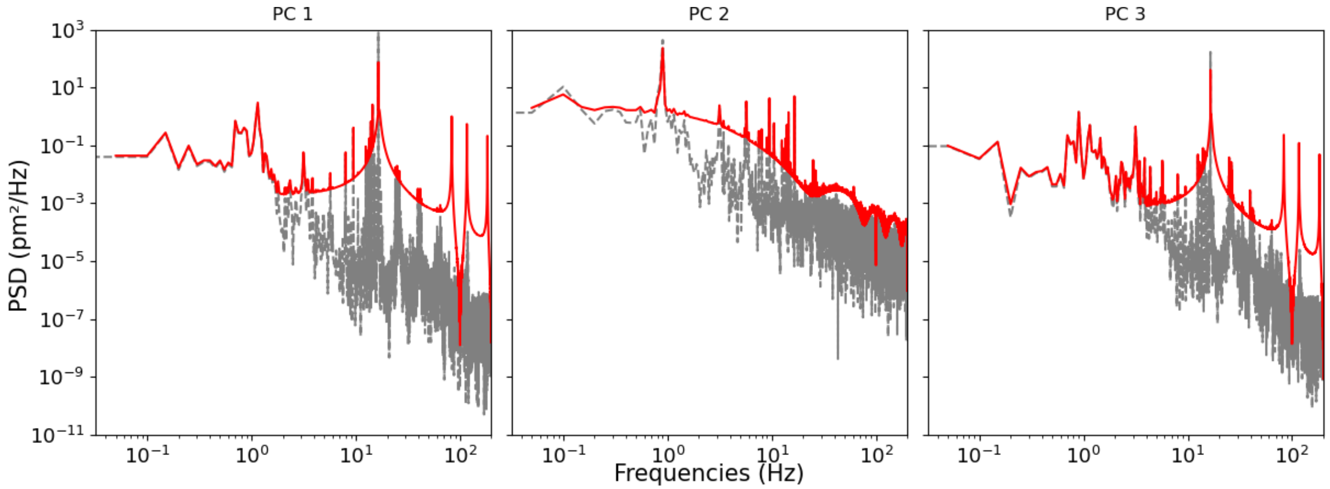
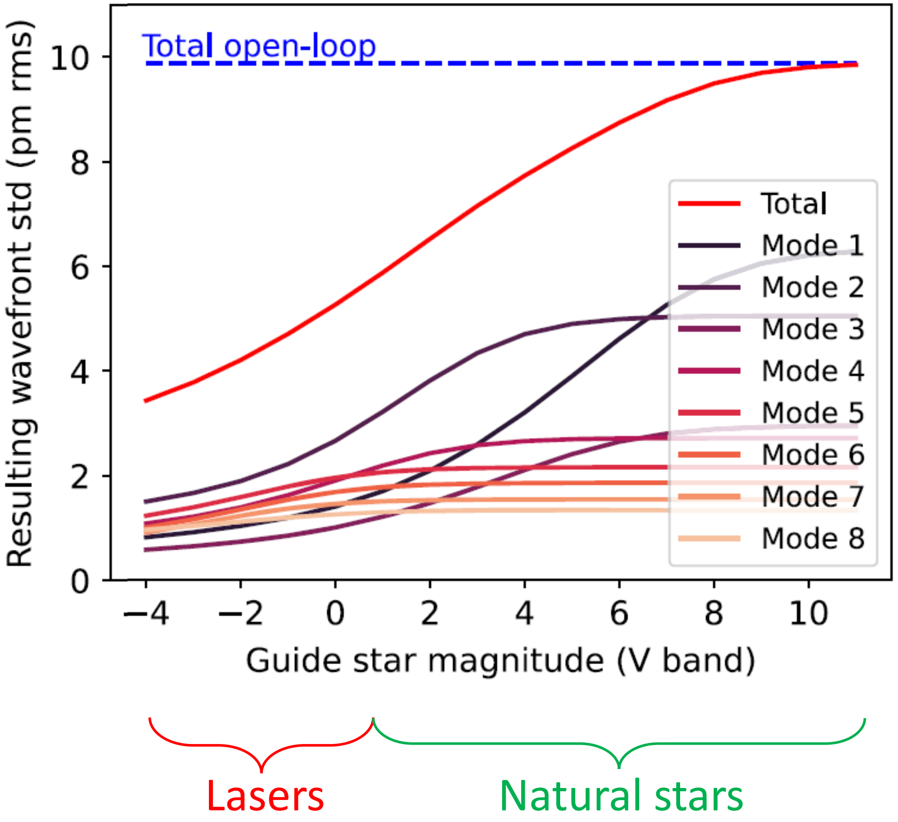


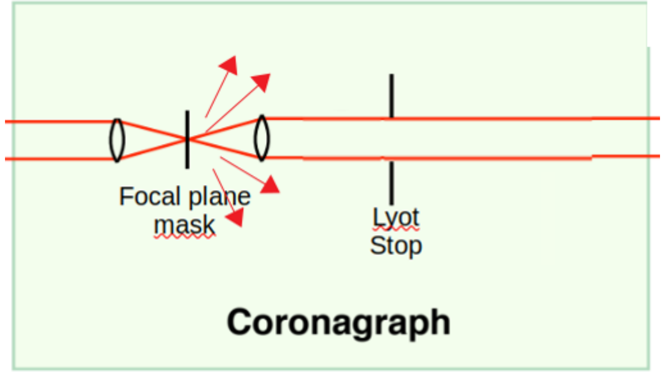




4) Post AO contrast performance

a) Instant contrast calculation.

→ Takes about a week (Single core Intel 1.90GHz CPU)



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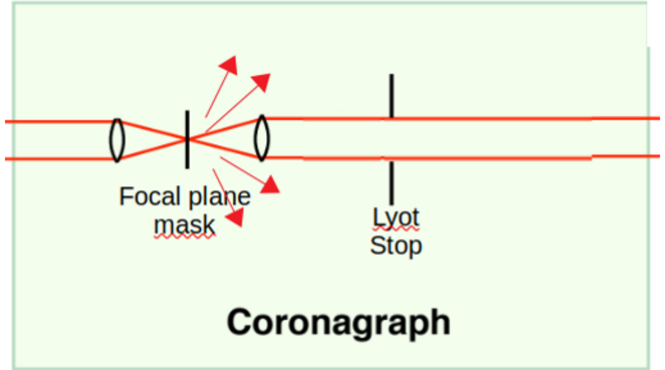

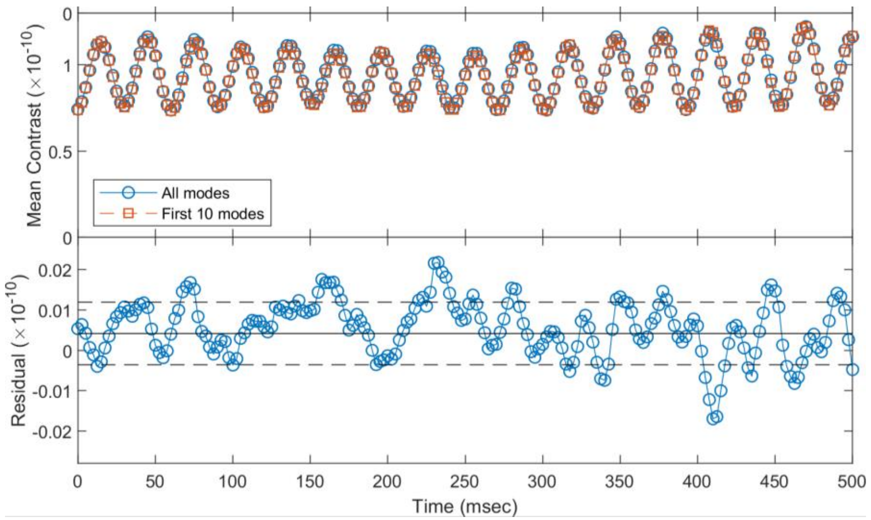

→ The total contrast is dominated by the contrast of the 10 principal components!

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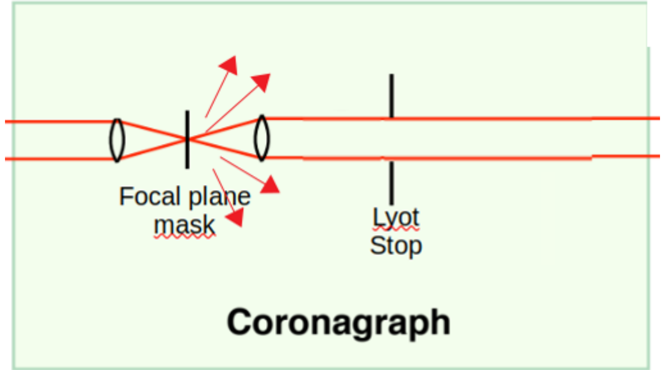

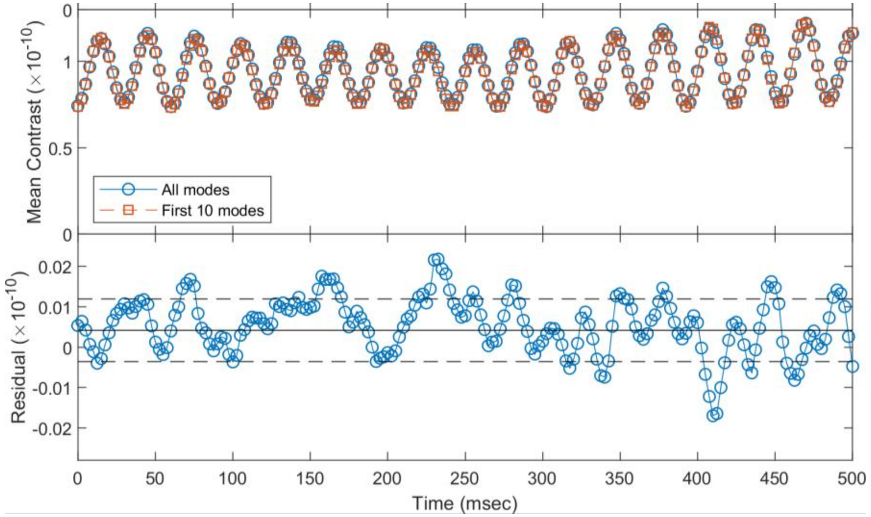

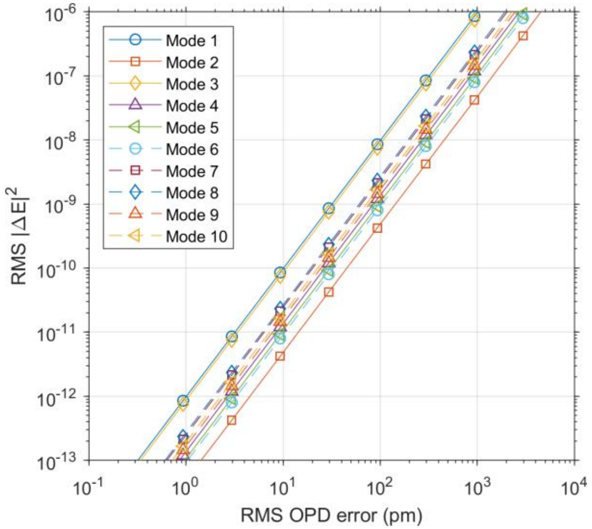

→ The total contrast is dominated by the contrast of the 10 principal components!

→ Quadratic relationship between intensity and error std

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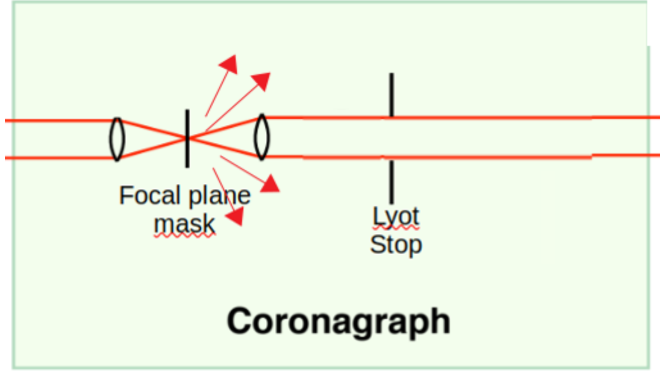

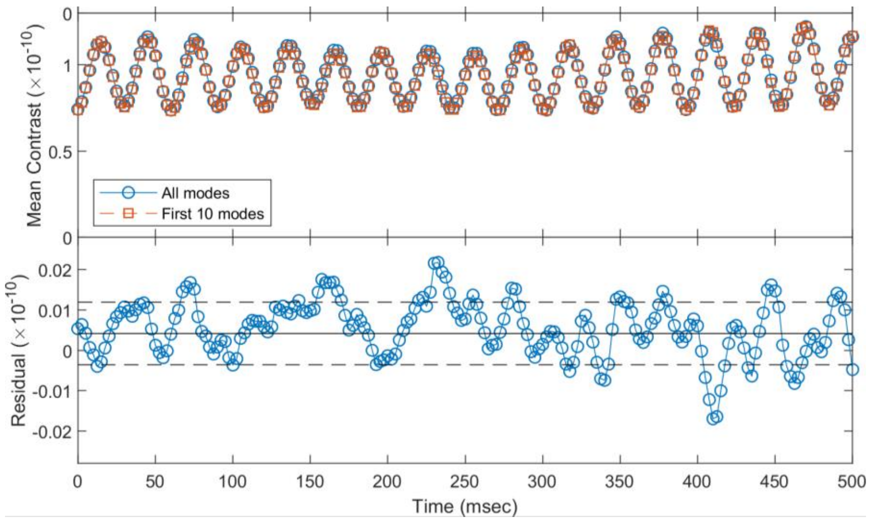

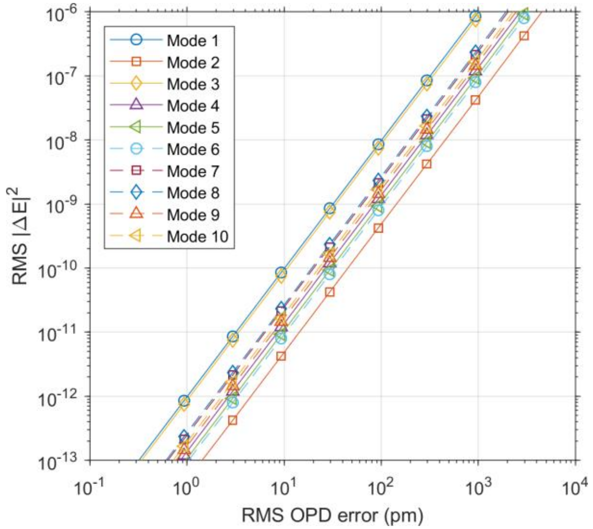

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→ Quadratic relationship between intensity and error std

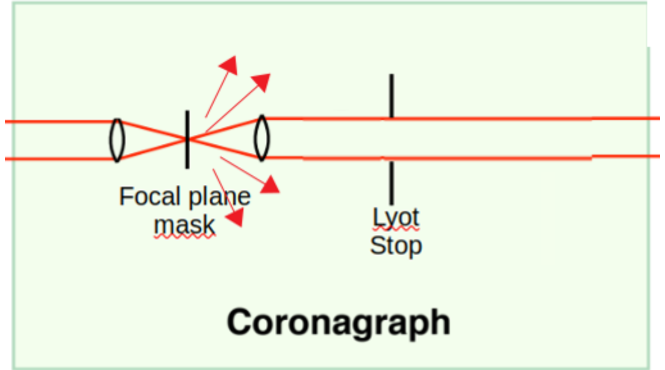
SOLUTION

$$I(t) = \left| E_0 + \sum_{i=1}^{10} a_i(t)\Delta E_i \right|^2$$

→ Takes about 50s

4) Post AO contrast performance

b) Long-exposure contrast calculation.

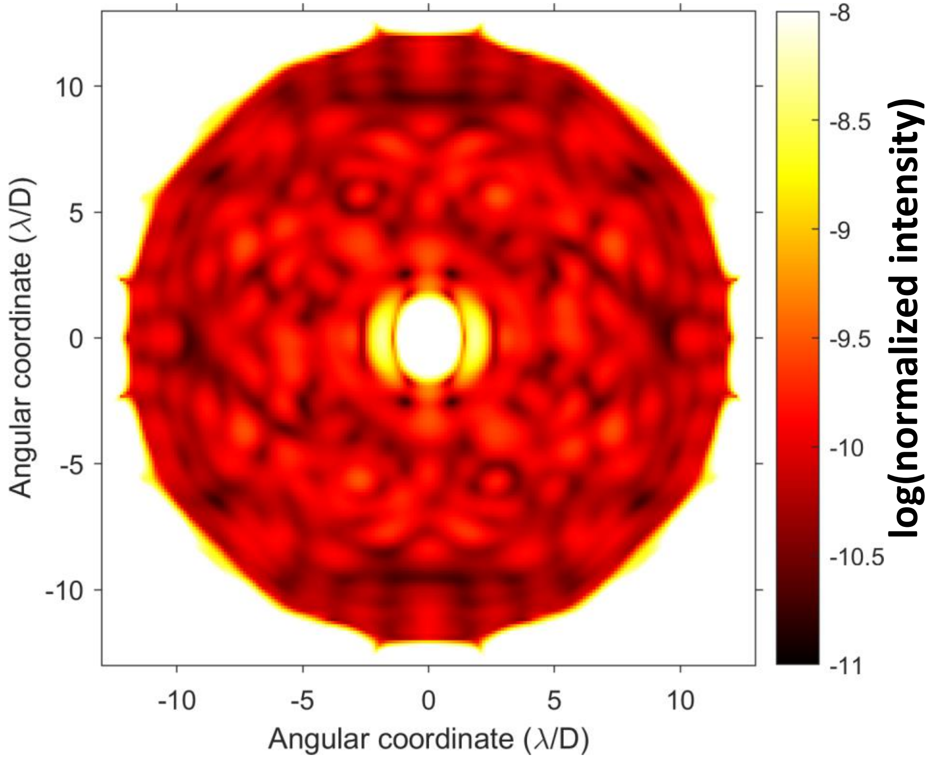


$$\langle I \rangle = |E_0|^2 + 2\sum_{i=1}^{10} \langle a_i \rangle Re(E_0^* \Delta E_i) + \sum_{i=1}^{10} \sum_{i'}^{10} \langle a_i a_{i'} \rangle \Delta E_i \Delta E_{i'}$$

With statistical assumptions:

- Zero mean : $\langle a_i \rangle$=0
- Modes uncorrelated : $\langle a_i a_{i'} \rangle$=0 if i≠I'

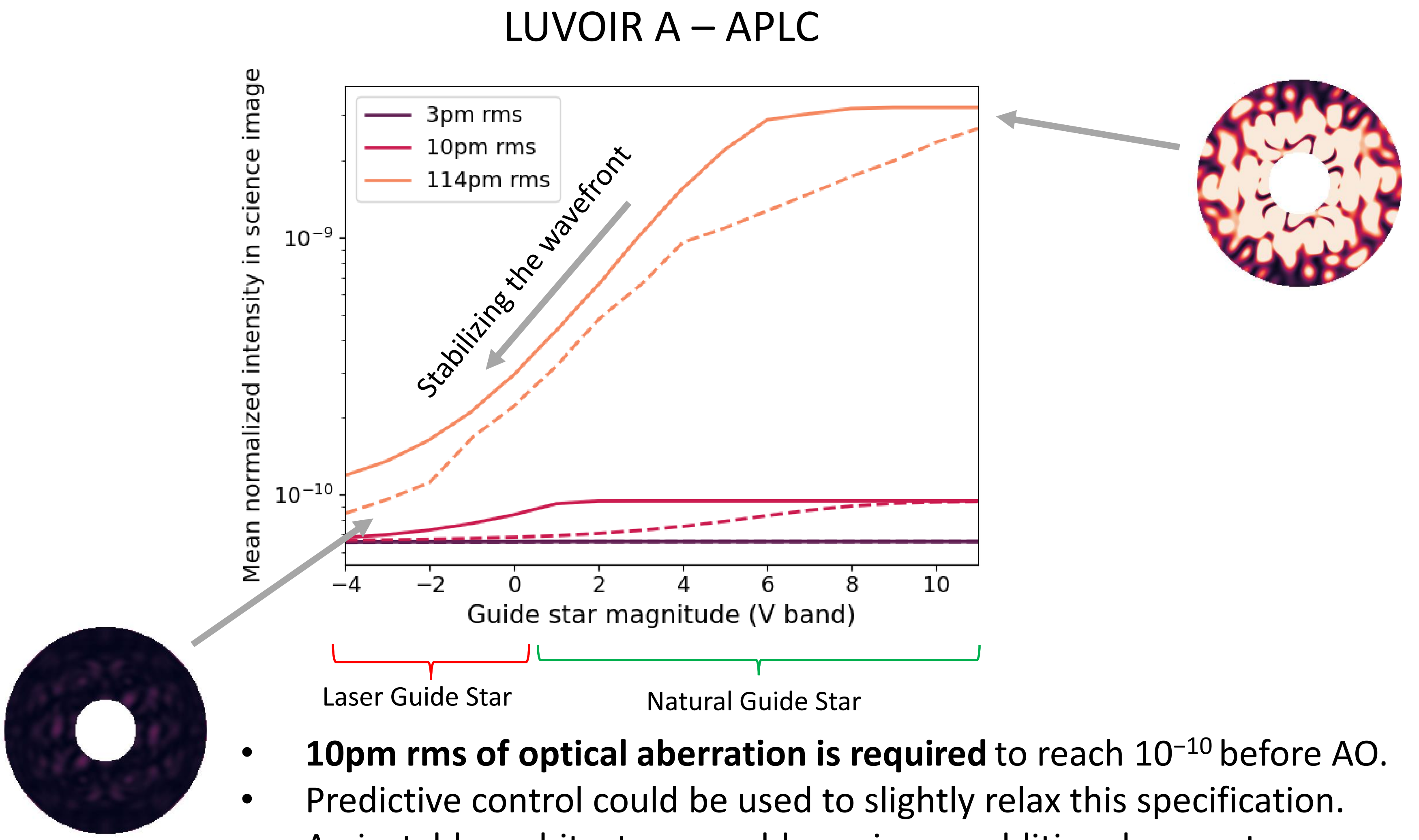
$$\langle I \rangle = |E_0|^2 + \sum_{i=1}^{10} \langle a_i^2 \rangle |\Delta E_i|^2$$

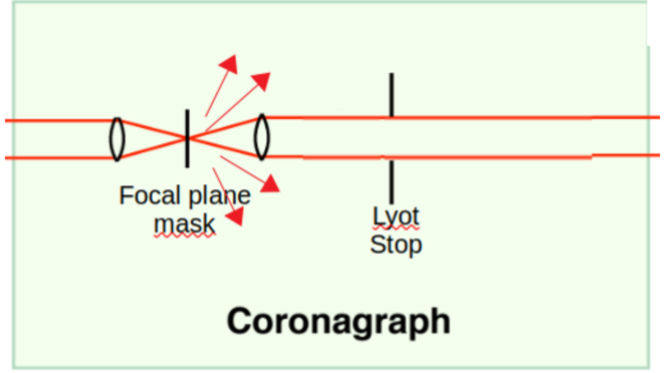


→ Takes about 1s

4) Post AO contrast performance

c) Results



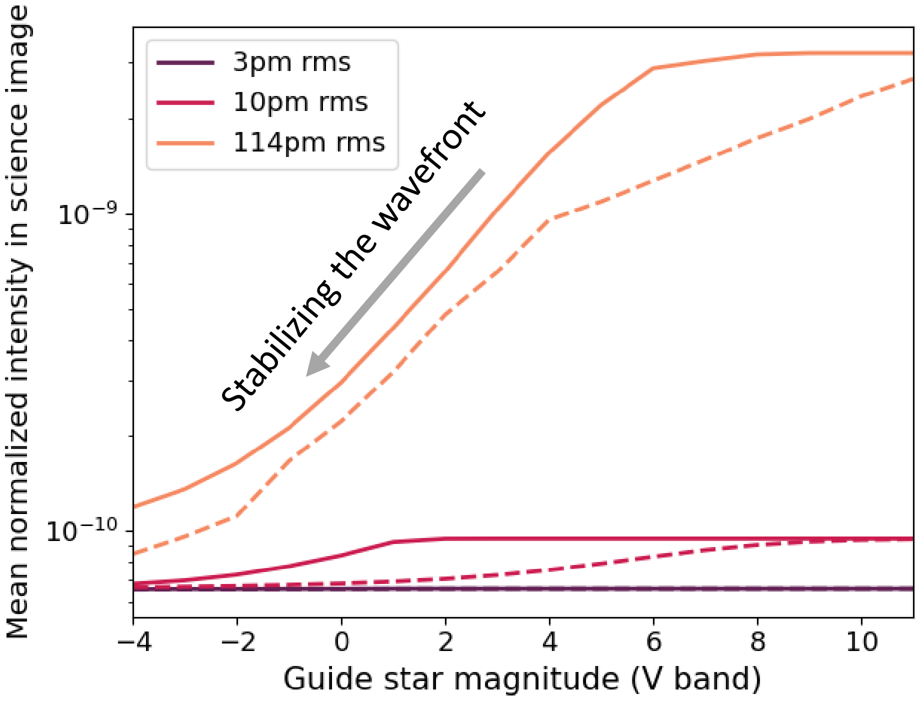


- **10pm rms of optical aberration is required** to reach 10^{-10} before AO.
- Predictive control could be used to slightly relax this specification.
- An instable architecture would require an additional separate spacecraft as a laser guide star to fully preserve yield.

4) Post AO contrast performance

c) Results

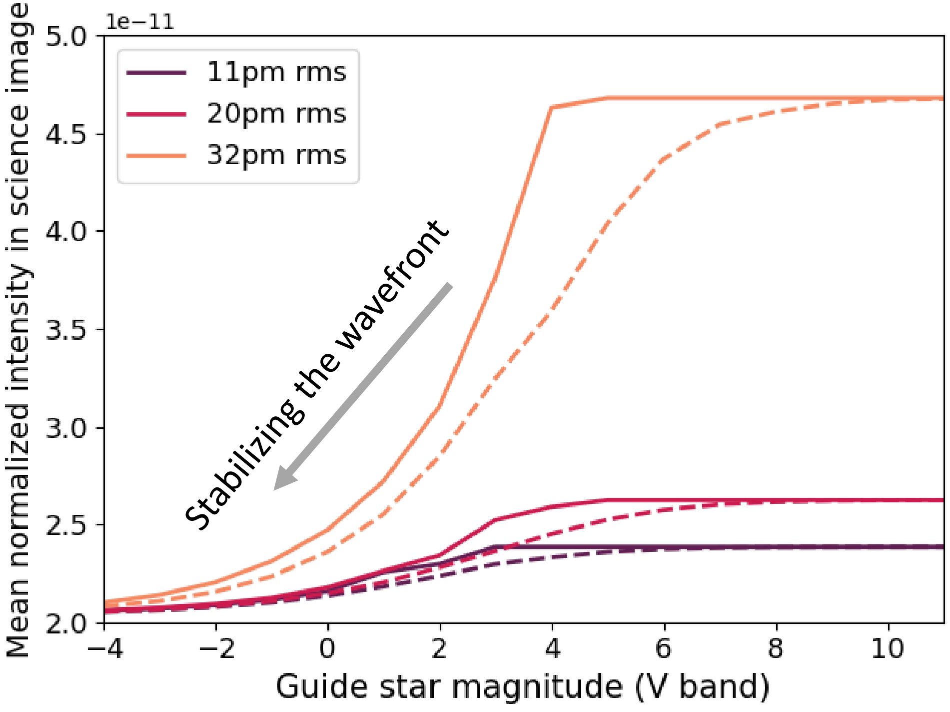
LUVOIR A – APLC



Laser Guide Star

Natural Guide Star

LUVOIR B – Apodized vortex charge 6



Laser Guide Star

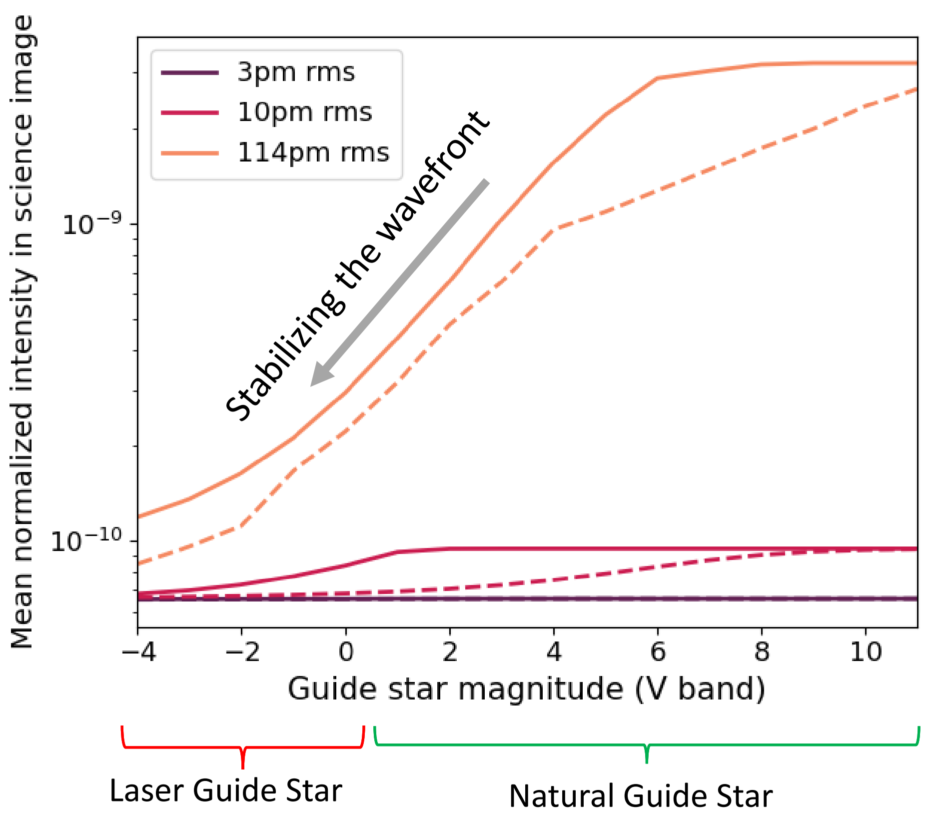
Natural Guide Star

- LUVOIR-B structural modes are dominated by spatially low-order components **well rejected by the DM-AVC**.
- Assuming linearity between contrast and modal variance, the dynamical aberration error budget can be increased to **~55pm rms to keep the contrast under 10^{-10}** .
- Corresponds to a factor ~5 relaxation in std (25 in variance) with respect to LUVOIR A + APLC.

4) Post AO contrast performance

c) Results

LUVOIR A – APLC



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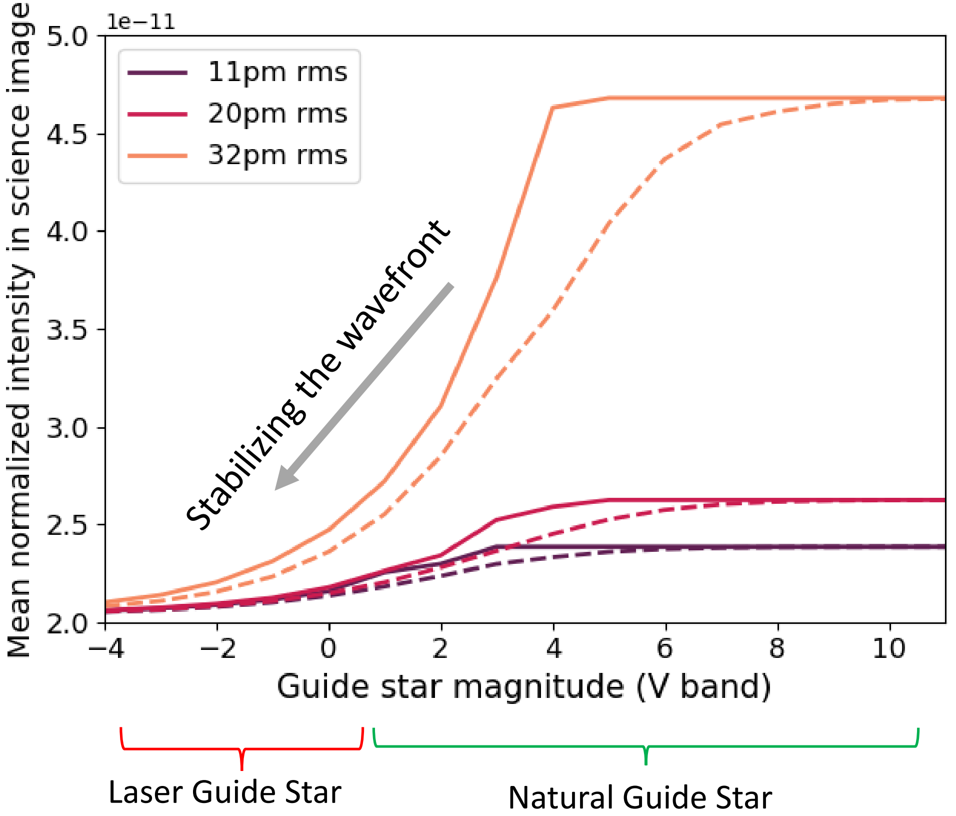


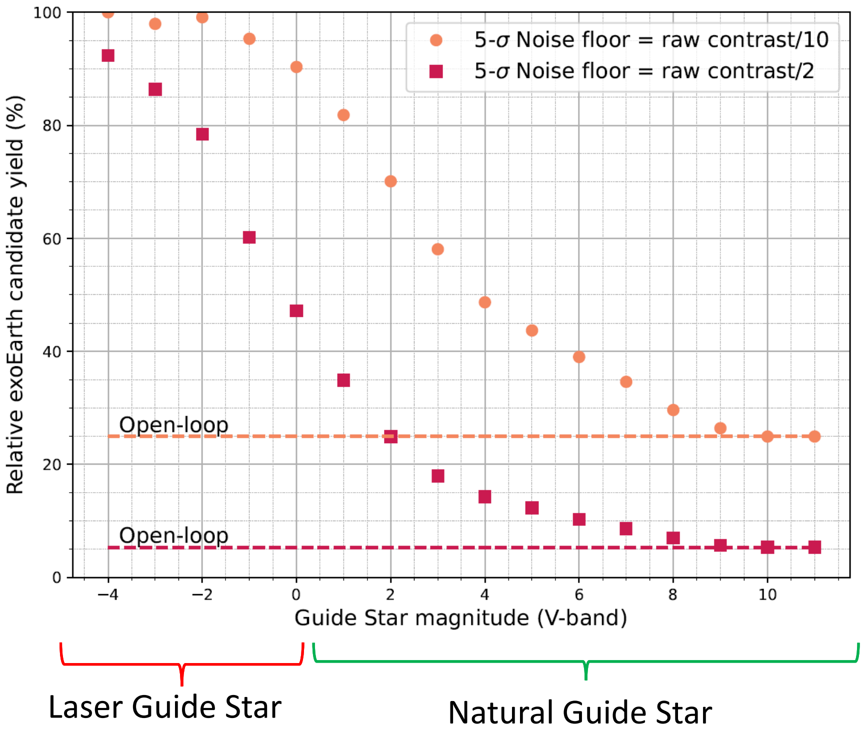
- **LUVOIR-B offers better observing conditions for a coronagraph**: AO is “useless” with the provided time series since ideal yield (~25 exoEarths candidates) should be reached for any simulated case.
- The higher signal in the LUVOIR-B first modes **benefits the optimized integrator** at lower flux.
- The multiplicity of vibrations **penalizes the predictive controller**.

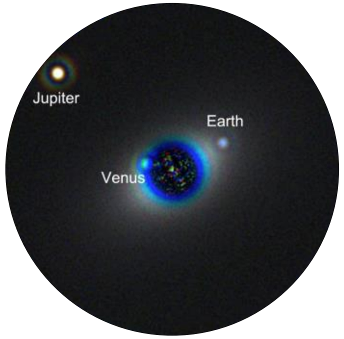
5) Yield gain of LUVOIR A with WS&C

a) AYO result using a laser guide star (~100pm rms case, predictive control)

Two regimes considered, depending on unknown postprocessing performance:

- The noise floor is **a tenth** of the raw contrast (optimistic, noiseless case for RST)
- The noise floor is **half** the raw contrast (more realistic, expected for RST)





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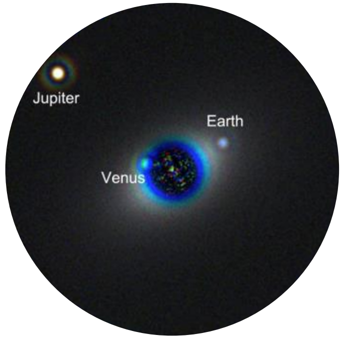

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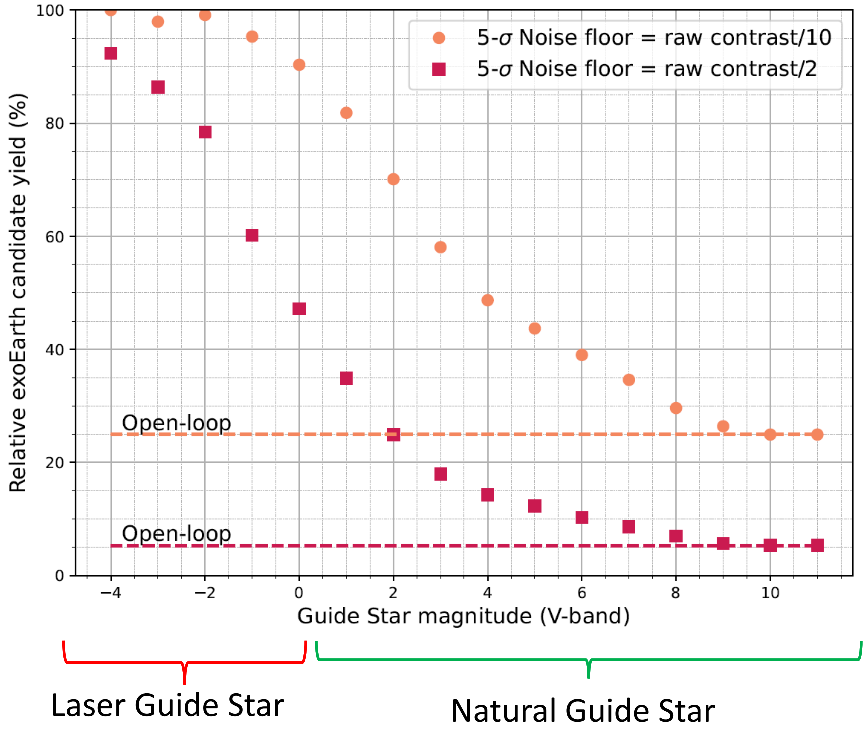
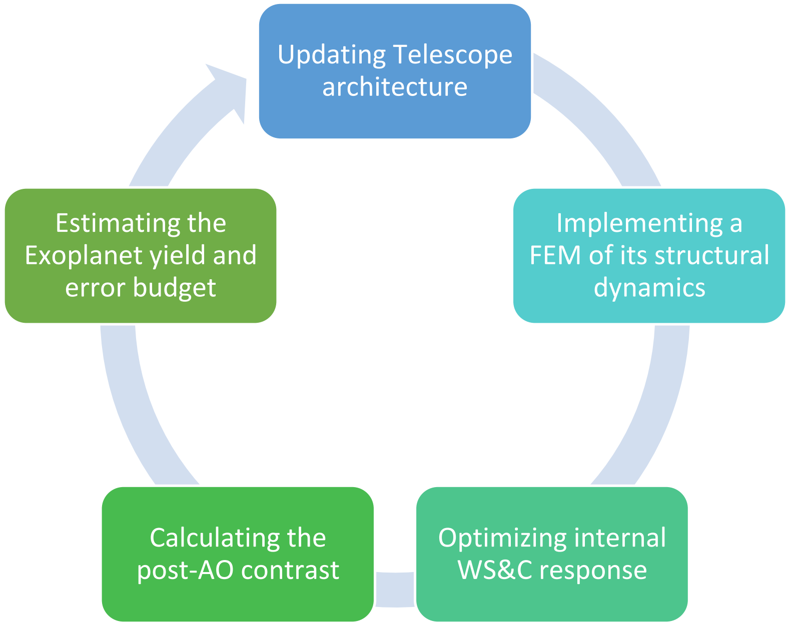


- Without WS&C, the yield loss in the ~100pm rms case is disastrous (**from 75% to 95% loss**)
- With WS&C, the use of a bright laser guide star allows to **recover a minimum of 50%** of the yield achievable without dynamical aberrations.
- **The yield performance with NGS remains unknown**. Between 60% to 95% loss when strongly limited by the noise floor. Between 20% and 75% loss with more optimistic postprocessing performance.

Conclusion and perspectives

- SCDA completed an **end-to-end analysis of LUVOIR-like missions**: including integrated telescope and coronagraph modeling and mission science yield estimates.
- This model is a key capability in **guiding technology development and system design**.
- **Adaptive Optics** may be essential for space-based exoplanet direct imaging applications to relax the stability requirements.
- **Predictive control** algorithm might be vital. Collaboration with the ground-based community is advised.
- The **temporal or spatial rms of the input dynamic aberrations are insufficient information** to derive coronagraph performance: both spatial and temporal analyses need to be performed.
- The IROUV optical telescope assembly and its coronagraph should be considered as a **single instrument** and designed **iteratively** to preserve yield.
- Semi-automatic tools are now available for such studies.



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