Non-linear low-order wavefront control with a physics-based digital twin: On-sky results from MagAO-X

No Neural Networks Required!

Matthijs Mars[1], S. Y. Haffert[1,2], J. R. Males[2], L. M. Close[2], K. Van Gorkom[2], O. Guyon[2,3,4,5], A. D. Hedglen[6], P. T. Johnson[2], M. Y. Kautz[2], J. K. Kueny[3], J. Liberman[3], J. D. Long[7], J. Lumbres[3], E. A. McEwen[3], A. McLeod[8], L. A. Pearce[9], L. Schatz[10], E. Tonucci[1], K. Twitchell[3]

1. Introduction

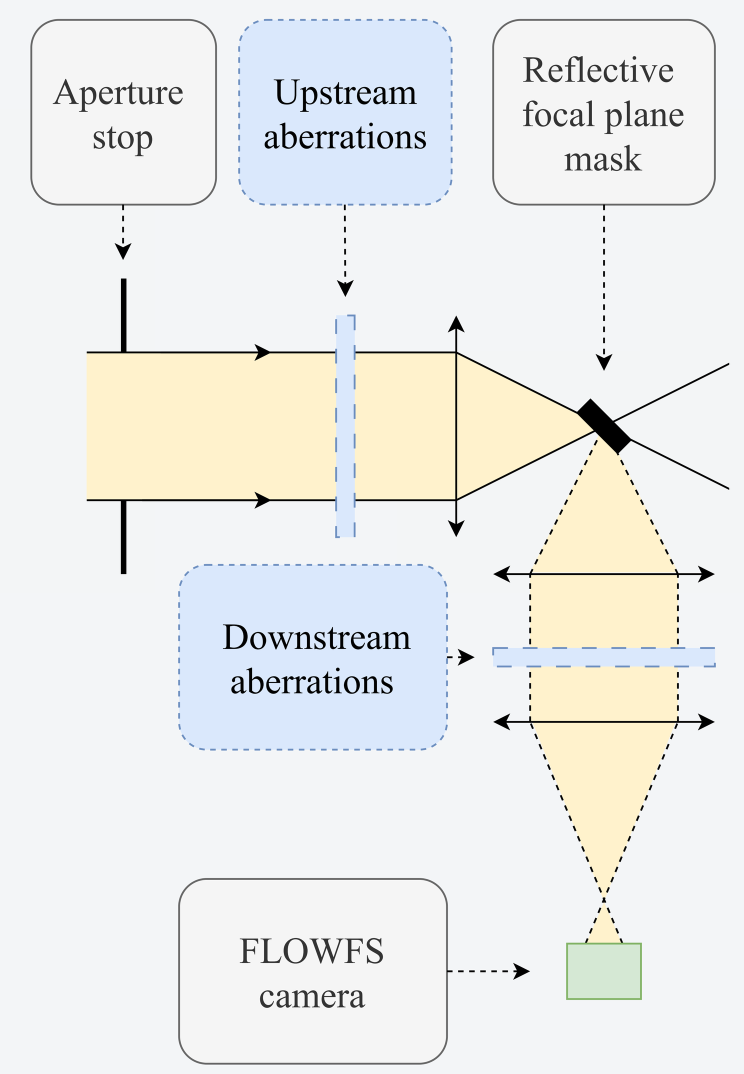
Low-order aberrations are one of the main limiting factors for coronagraphic performance in high-contrast imaging systems. These aberrations cause starlight leakage through the coronagraph, reducing contrast and sensitivity to faint companions and can be caused by:

- Residual atmospheric aberrations after high-order correction
- Telescope vibrations and bench seeing
- Slowly evolving non-common path aberrations (NCPA) due to e.g. thermal evolution

In order to reduce leakage and maintain high coronagraphic performance, low-order wavefront sensing and control is essential. In this work, we have developed a fully physical, fully differentiable digital twin of the focal plane low-order wavefront sensor (FLOWFS) on MagAO-X in order to provide:

- PSF sharpening by removing quasi-static NCPA
- Low-order real-time wavefront control to correct for residual aberrations and vibrations
- Accurate phase reconstructions that can be used for coronagraphic post-processing

2. FLOWFS in MagAO-X



Matthijs Mars
Postdoctoral researcher
Leiden Observatory
mars@strw.leidenuniv.nl

3. Digital twin model

We have developed a fully physical and fully differentiable digital twin of the FLOWFS system on MagAO-X. This model includes:

- Upstream aberrations (NCPA, residual atmospheric aberrations, vibrations)
- Reflection off the coronagraphic focal plane mask
- Downstream aberrations (NCPA, vibrations)
- Defocus in the wavefront sensor arm

4. Lab digital twin calibration

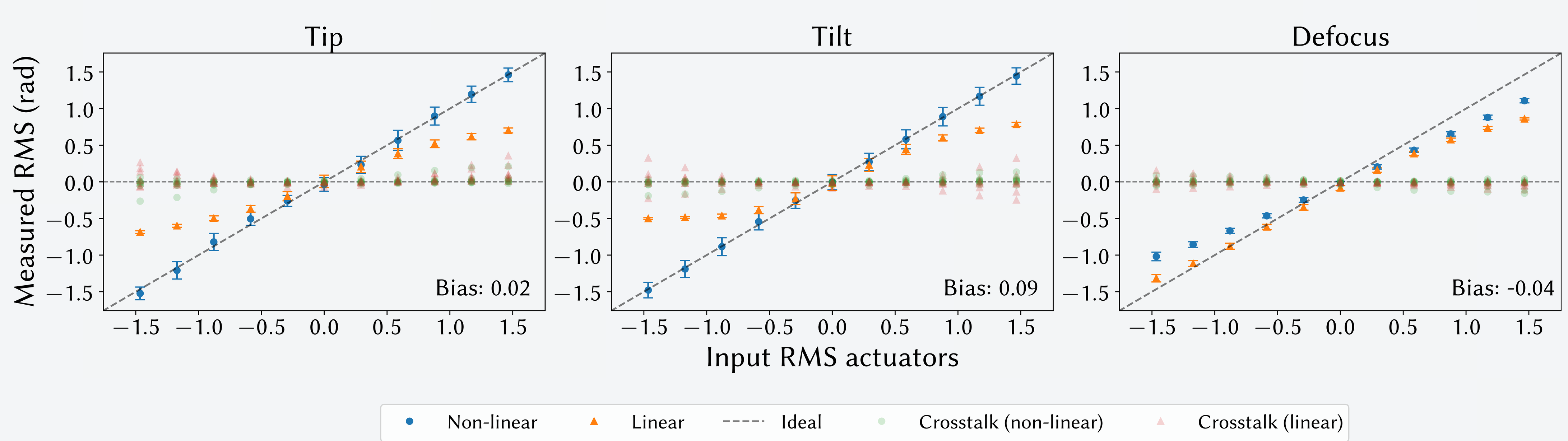


Figure 1: The digital twin is calibrated by sweeping through a series of low-order modes using the coronagraphic DM and fitting the model parameters to minimize the difference between the model and the measured images. Here we show the reconstructed modal coefficients for the first 3 out of 9 modeled Zernike modes in the lab using a small Lyot coronagraph (272μm). We show the reconstructions using the "slower" non-linear method as well as the fast linearised method that is used for real-time control.

5. Phase reconstruction accuracy

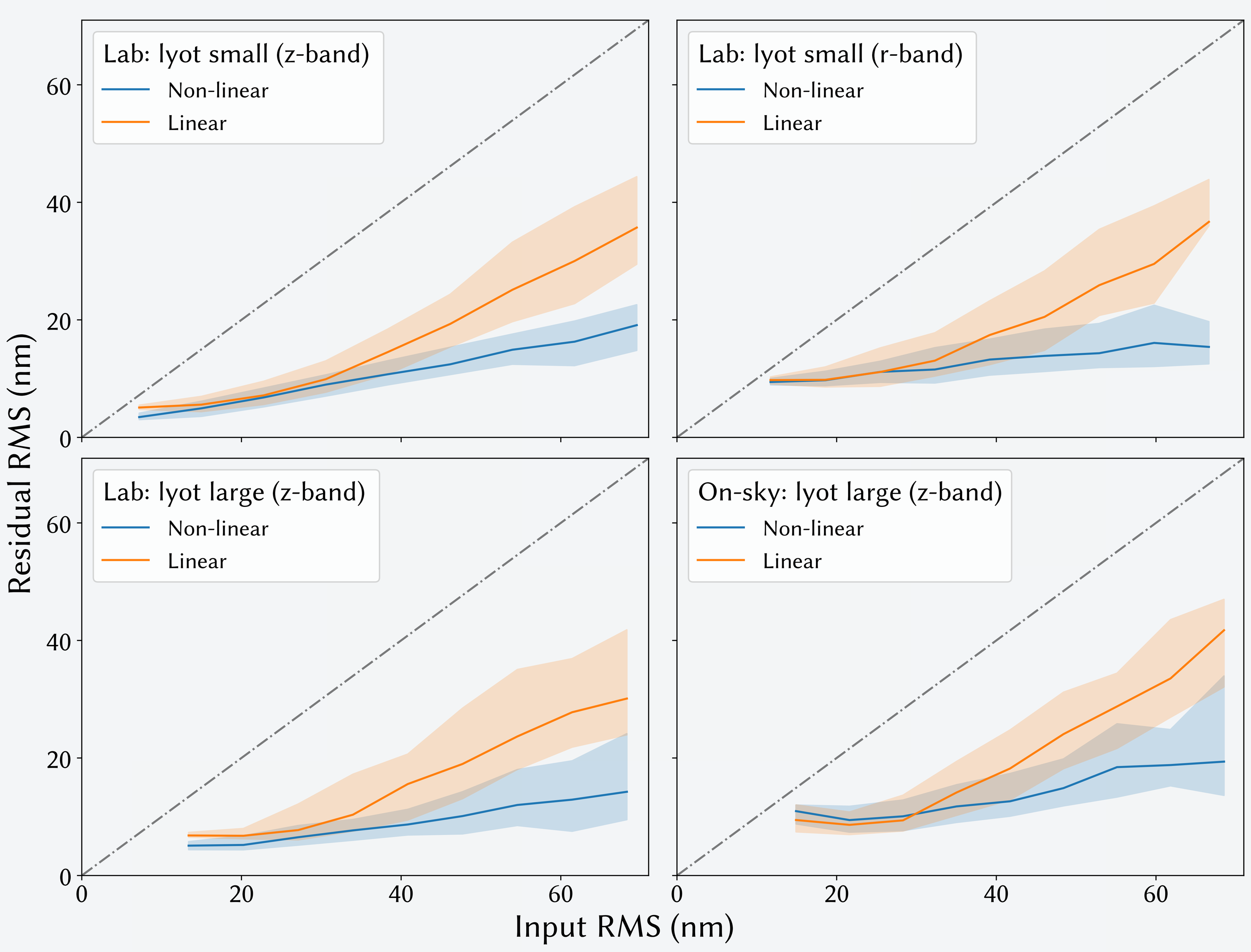


Figure 2: Lab reconstructions of input aberrations using our digital twins allows to get accurate phase estimates and easy switching between different coronagraphic masks and filters. And because it is fully physical, it transfers to on-sky data with minimal changes.

6. On-sky real-time control at 8 kHz

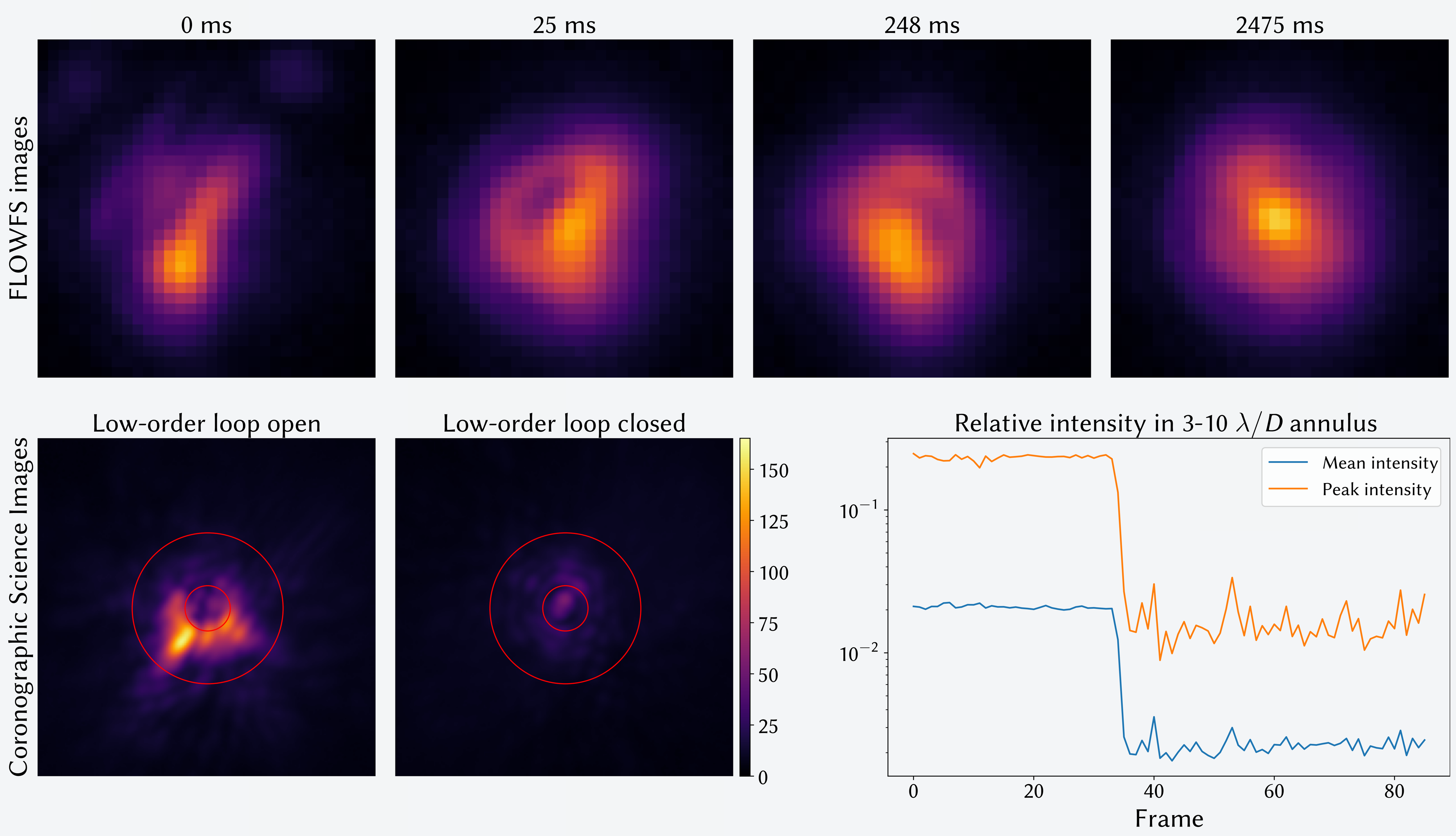


Figure 3: On-sky demonstration of closing the low-order wavefront control loop at 8 kHz using the model-based linear reconstructor. The top row shows the FLOWFS images, and the bottom row shows the coronagraphic science images as well as the leakage in the 3 to 10 λ/D region of interest.

7. Conclusions

We have developed and deployed a fully physical and fully differentiable digital twin of the FLOWFS system on MagAO-X for low-order wavefront sensing and control. Key advantages of this approach are:

- Fast real-time low-order wavefront control at kHz speeds using a model-based linear reconstructor
- Fast model-based calibration (<1 minute) enables quick on-sky setup
- Easy switching between different coronagraphs, filters, and observing setups
- Accurate non-linear wavefront reconstruction for quasi-static NCPA tracking and coronagraphic post-processing through forward modelling
- Performance predictions and optimisation

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Affiliations
[1]Leiden Observatory, Leiden University
[2]Steward Observatory, The University of Arizona
[3]Wyant College of Optical Sciences, The University of Arizona
[4]Subaru Telescope, National Observatory of Japan, National Institutes of Natural Sciences
[5]Astrobiology Center, National Institutes of Natural Sciences
[6]Northrop Grumman Corporation
[7]Center for Computational Astrophysics, Flatiron Institute
[8]Draper Laboratory
[9]Department of Astronomy, University of Michigan
[10]Starfire Optical Range, Kirtland Air Force Base