Design and modeling of the off-axis parabolic deformable (OPD) mirror laboratory

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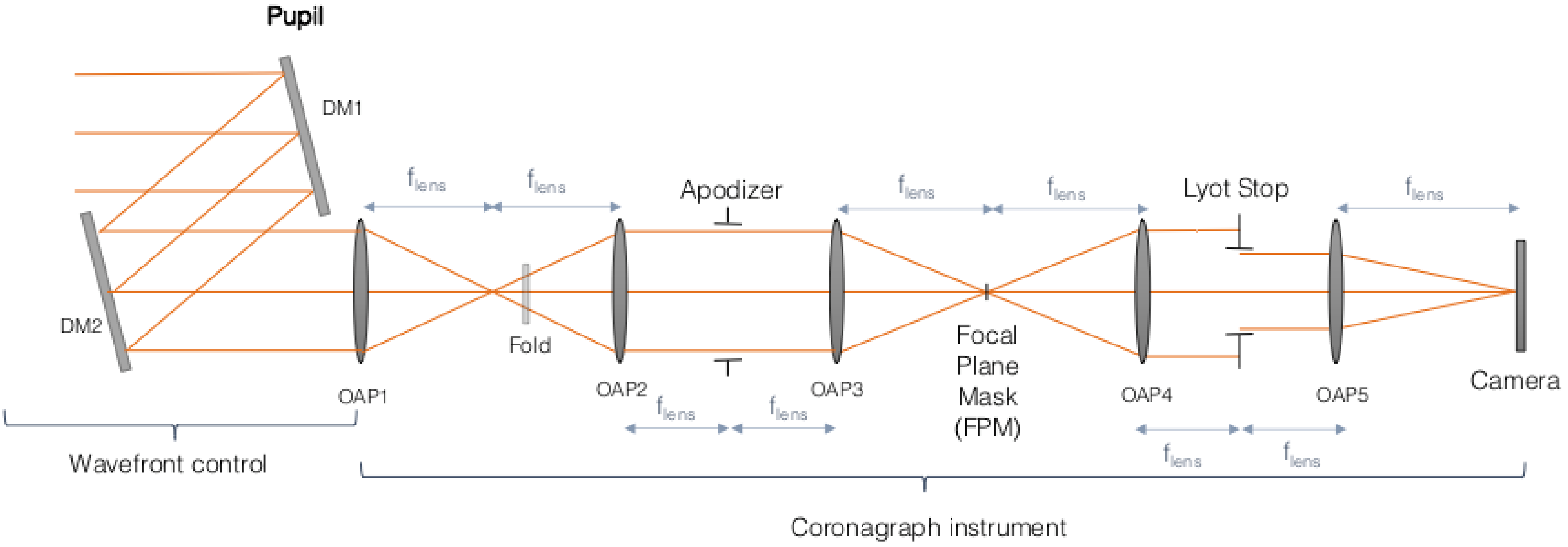
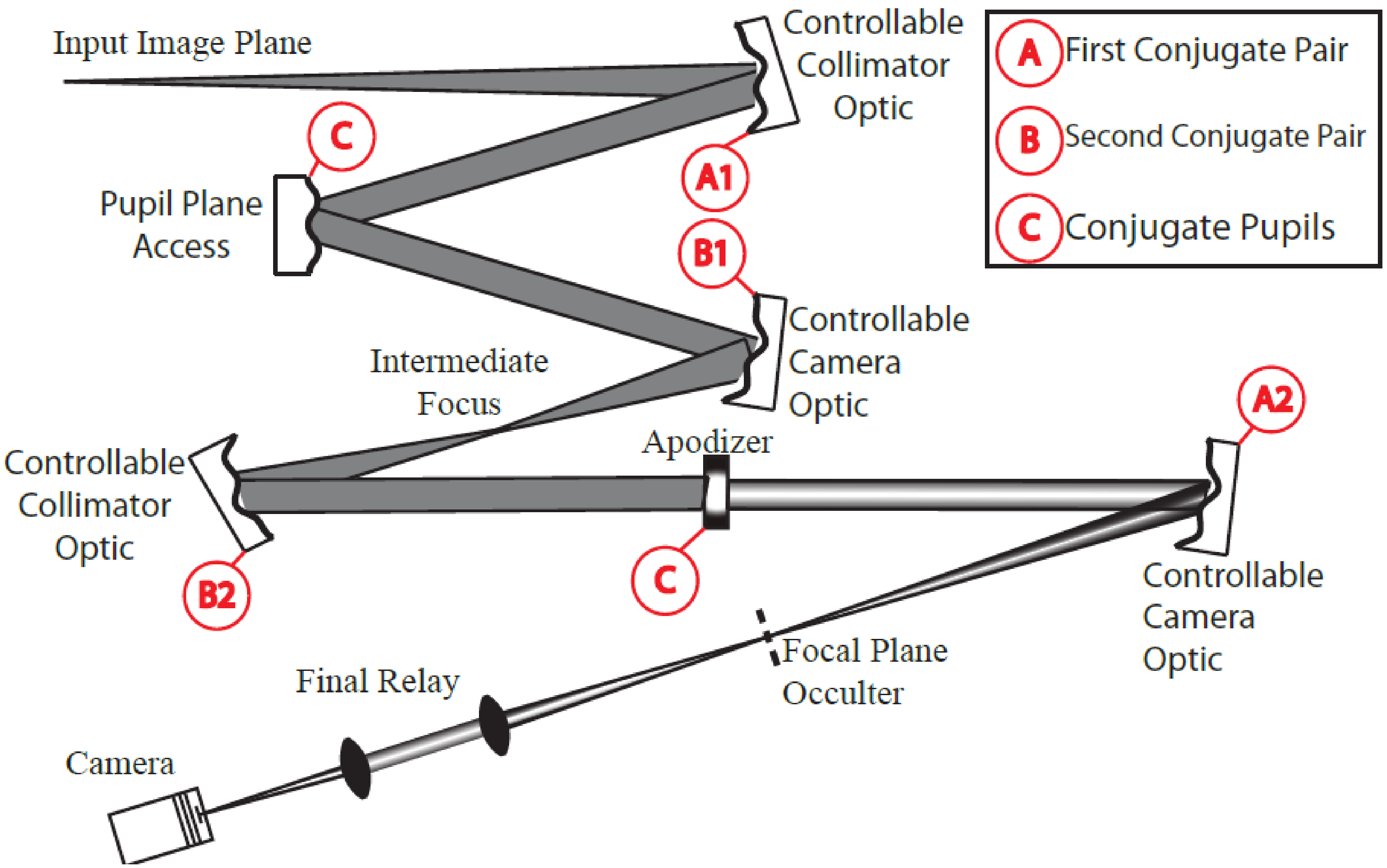
Coronagraph Optical Train (LUVOIR)



- Need 2 deformable mirrors (DMs) for wavefront sensing and control
- Long separation between DMs for amplitude and phase mixing
- High actuator count DMs

Issues:
Packaging issues
Higher risk of actuator failure

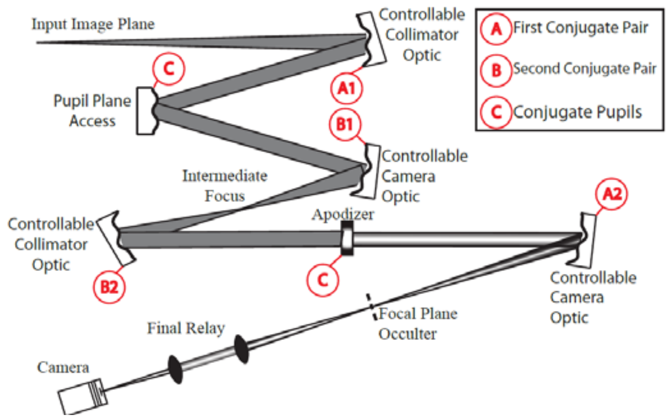
Low Actuator Count Parabolic DMs



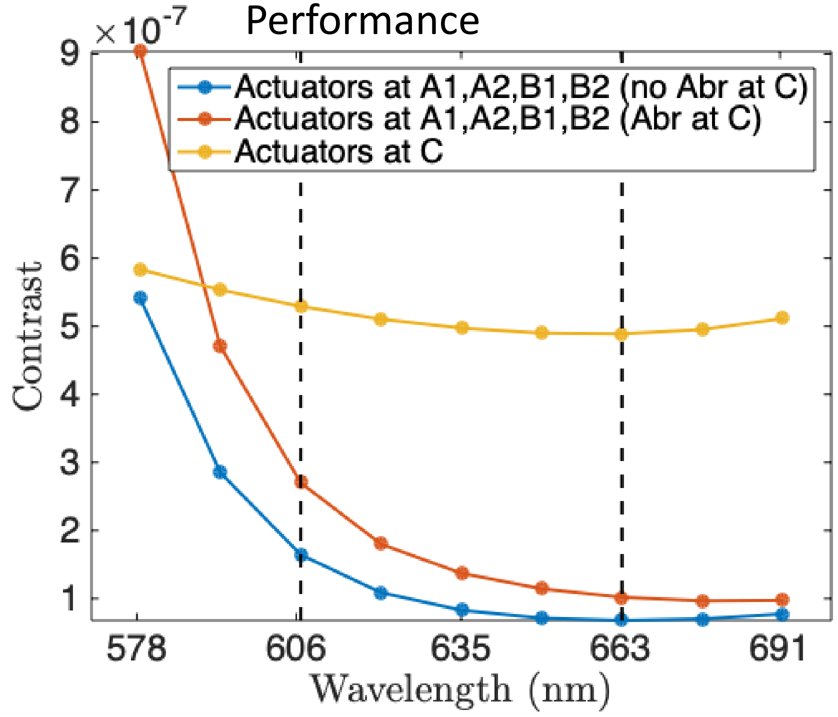
Groff et al. 2016

Comparing Broadband Performance

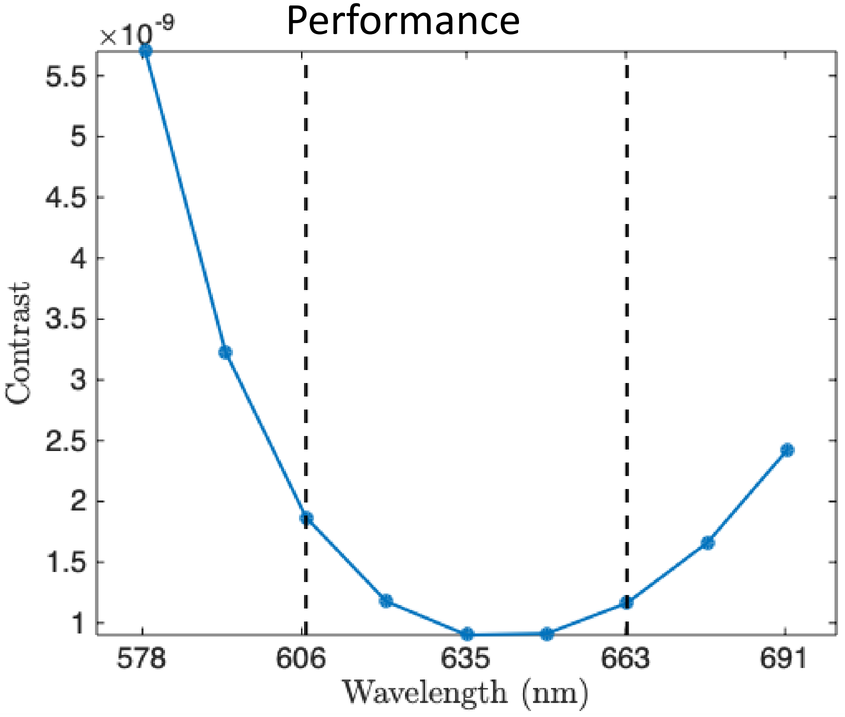
Experiment	Center Contrast	10% Average	20% Average
DM at Plane C	4.974×10^{-7}	5.033×10^{-7}	5.178×10^{-7}
DMs at A1,A2,B1,B2, Aberr. at C	1.374×10^{-7}	1.609×10^{-7}	2.636×10^{-7}
DMs at A1,A2,B1,B2, No Aberr. at C	8.30×10^{-8}	9.92×10^{-8}	1.634×10^{-7}



Individual Performance



Combined Performance



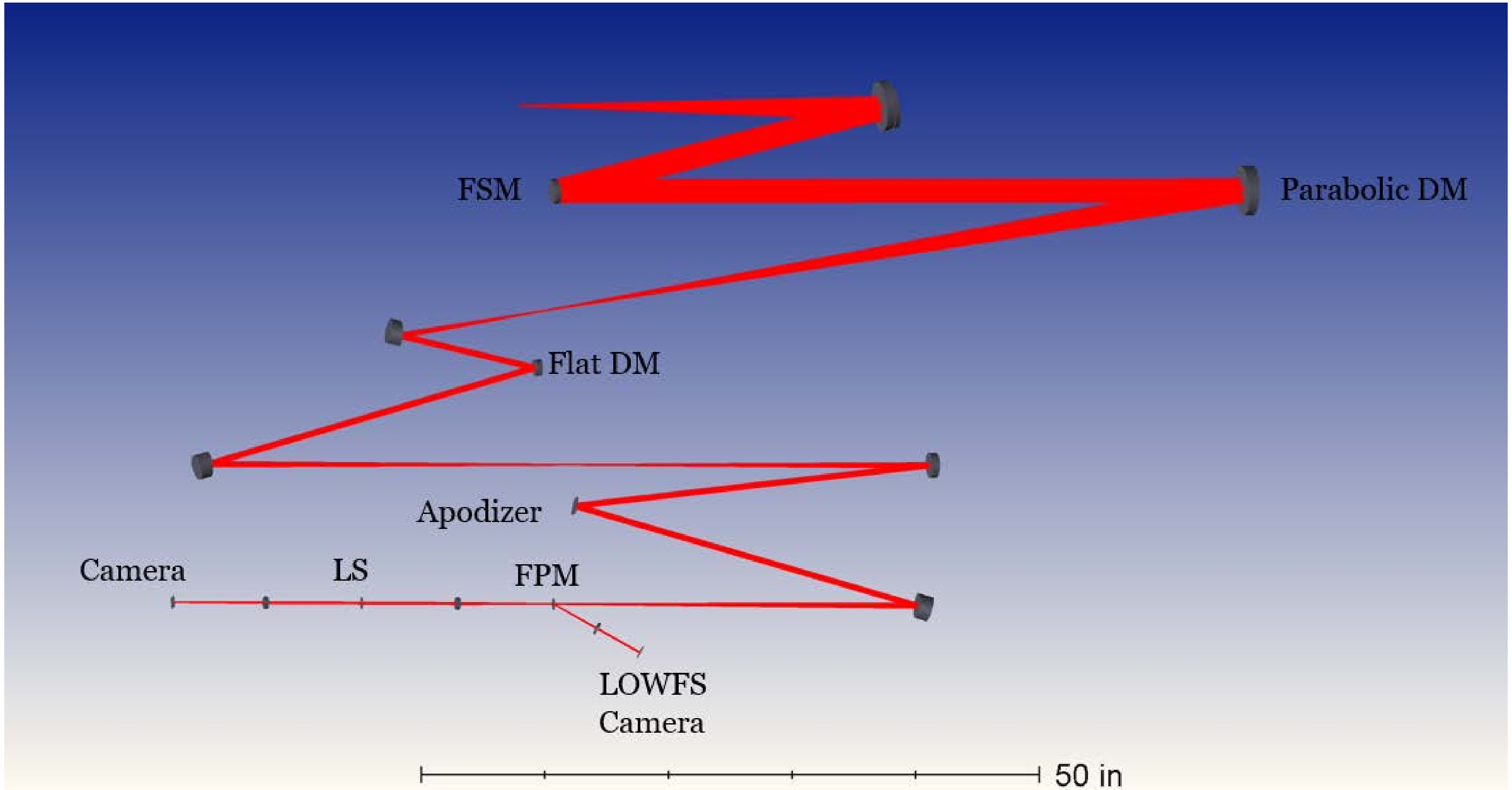
Groff et al. 2016

Advantages of Parabolic DMs

- Simplifies the packaging issue for space missions
- Reduces both cost and risk of having the entire coronagraph instrument’s performance depending on one or two high-actuator count DMs
- Increase in achievable bandwidth correction

    - Controllable surfaces are in conjugate planes to the sources of aberrations.

Lab layout NASA Goddard

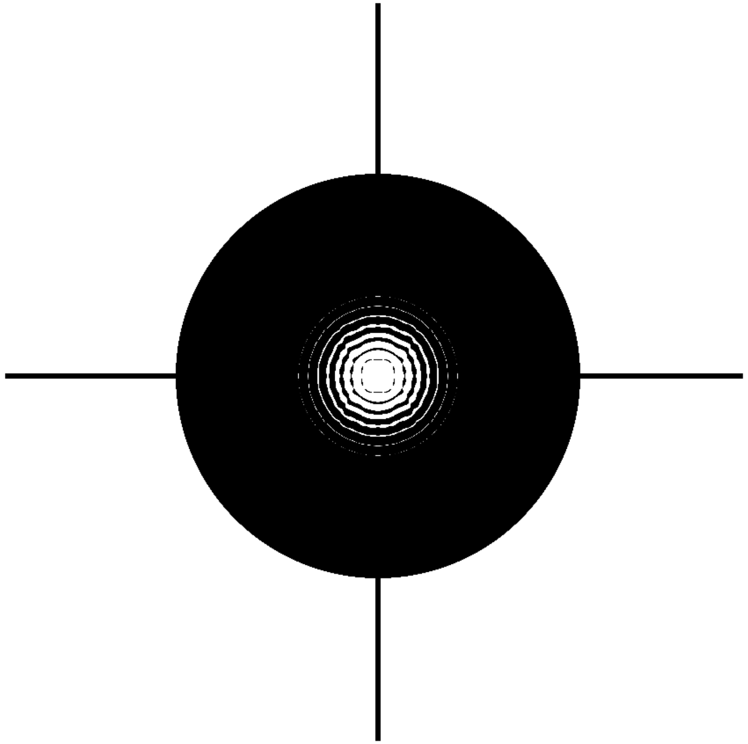


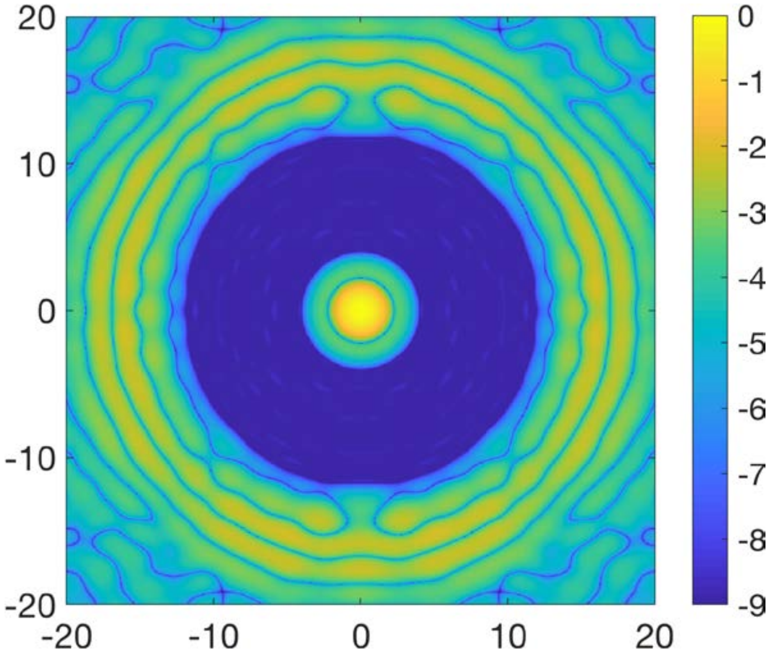
Instrument Details

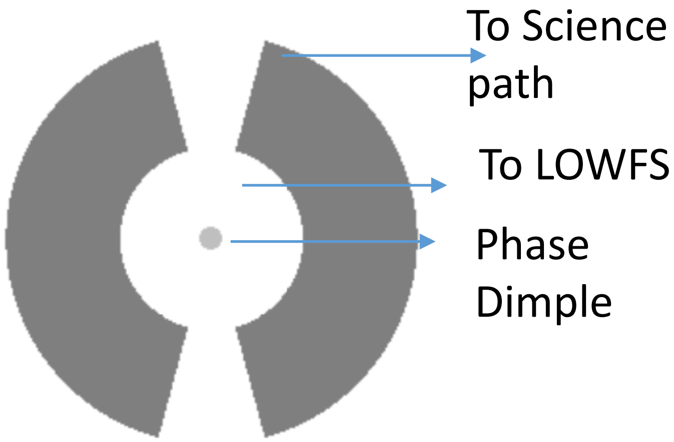
- Coronagraph

PSF

Focal Plane/ Zernike Mask







Instrument Details

- Flat Pupil DM

 - BMC 32 x 32 DM

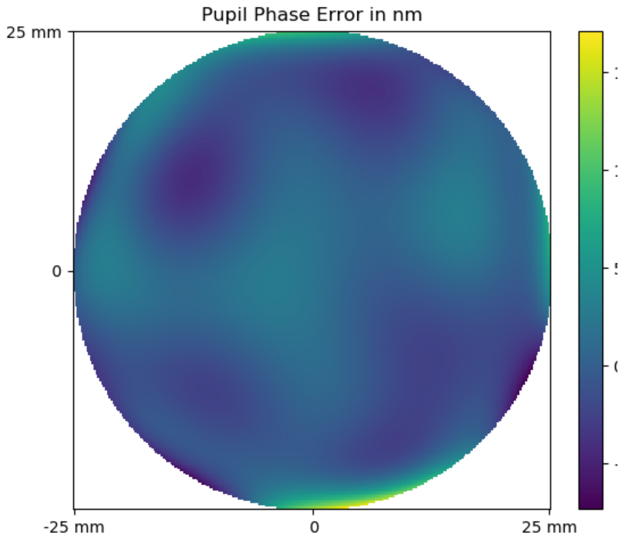
- Parabolic DM

 - Modified ALPAO 11 x11 DM

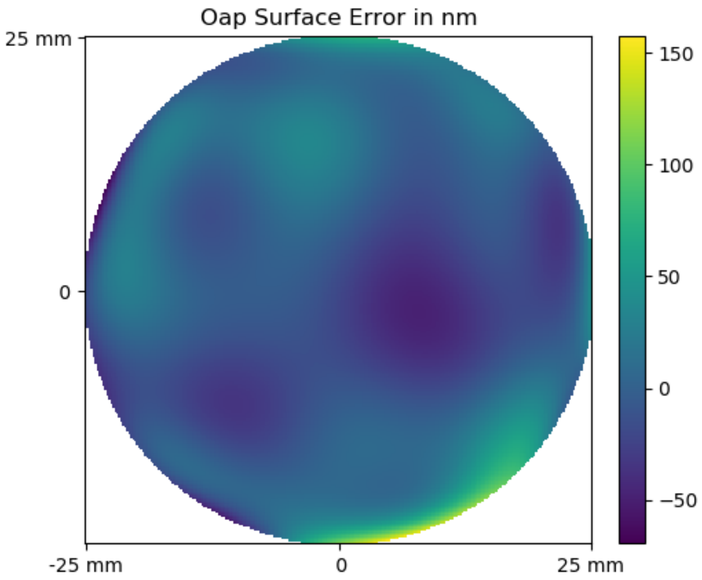
DM simulations

- Actuator resolution
  - Round up to nearest 10 pm or 100 pm
- Stability
  - Percent stability of the voltage/amplitude applied
  - 0.5%, 1%, and 2%
- Bandwidth 20%
- Assumptions:
  - Perfect Estimation
  - No amplitude aberrations

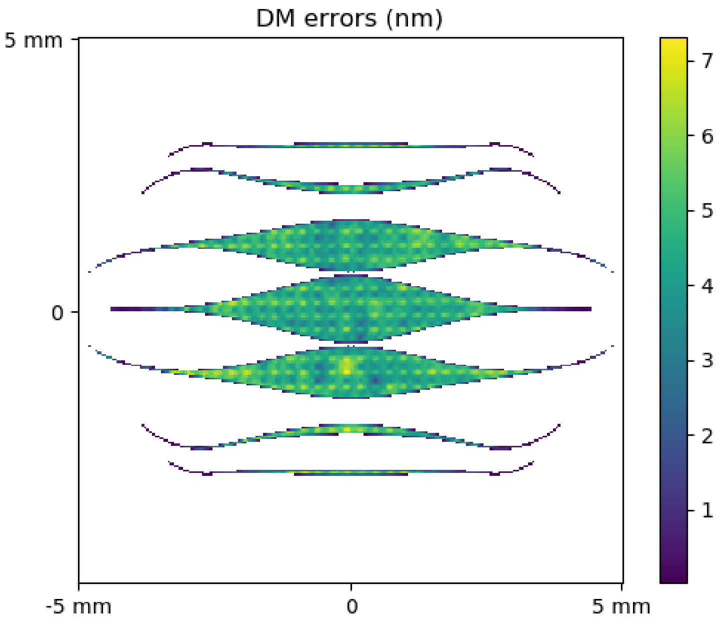
Error Maps Used for Simulation



a) Pupil Error Map (nm)



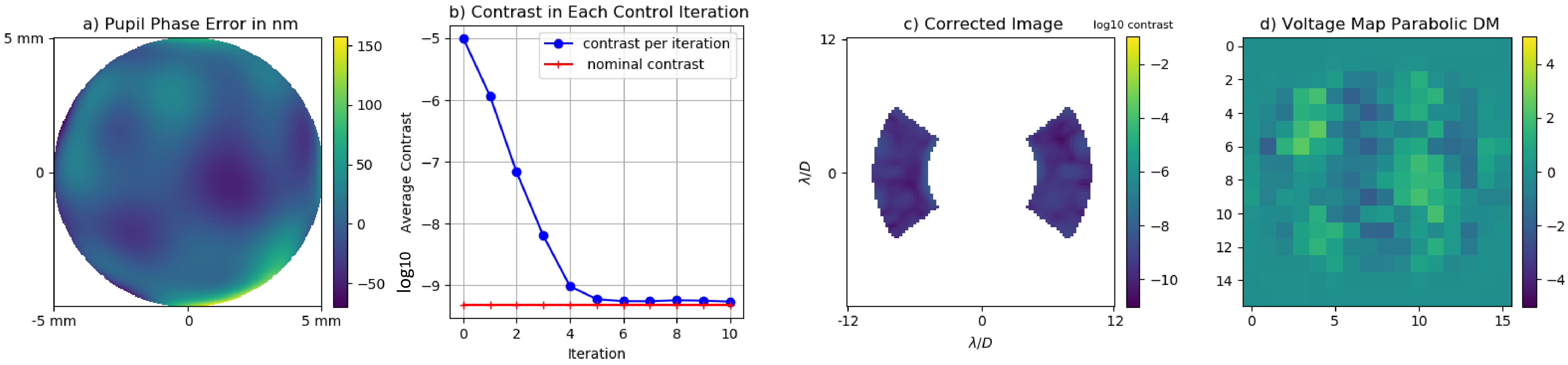
b) Parabolic DM Surface Errors (nm)



b) Flat DM Surface Errors (nm)

Selected Design Requirements and Result

- Stability of 0.5% and actuator resolution of 0.1 nm



Other Experiments

- The lab is multipurpose and following experiments to be carried out
  - Non-linear dark hole digging
  - Adaptive estimation of line-of-sight jitter (LOS)
  - Machine learning for LOWFS

Linear vs Non-linear Control

Linear Estimation and Control

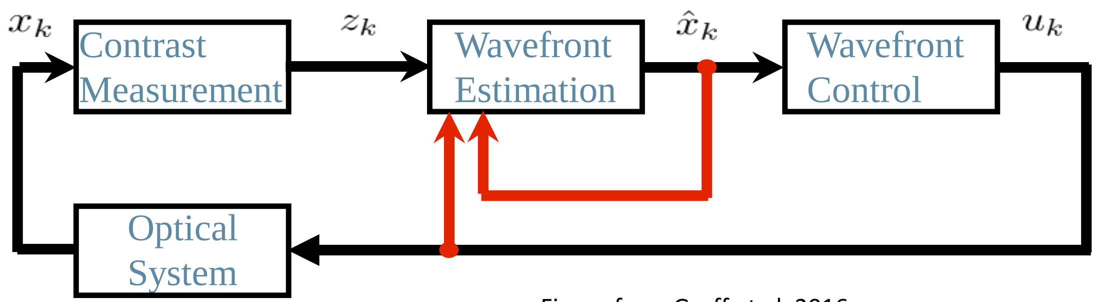


Figure from Groff et al. 2016

$$z = Hx + n$$
$$\hat{x} = (H^T H)^{-1} H^T z$$

$$W_k = (G_k u_k - \delta E_k)^T (G_k u_k - \delta E_k) + \alpha_k^2 u_k^T u_k$$
$$u_{\mathrm{w},k} = (G_k^T G_k + \alpha_k^2 \mathcal{I})^{-1} G_k^T \delta E_k.$$

Non-linear control

$$minimize\ W = \sum_{DH} I\ , where$$
$$I = f(A_{abb}, \Phi_{abb}, V_{DM})$$
$$= \left|A_{im} e^{\Phi_{im}}\right|^2$$
$$W = \sum_{DH} |A_{im} e^{\Phi_{im}}|^2$$
$$= \sum_{DH} A_{im}^2$$

Estimation : A_{abb}, Φ_{abb}
Control : Just need a single DM?!

Non-linear Control

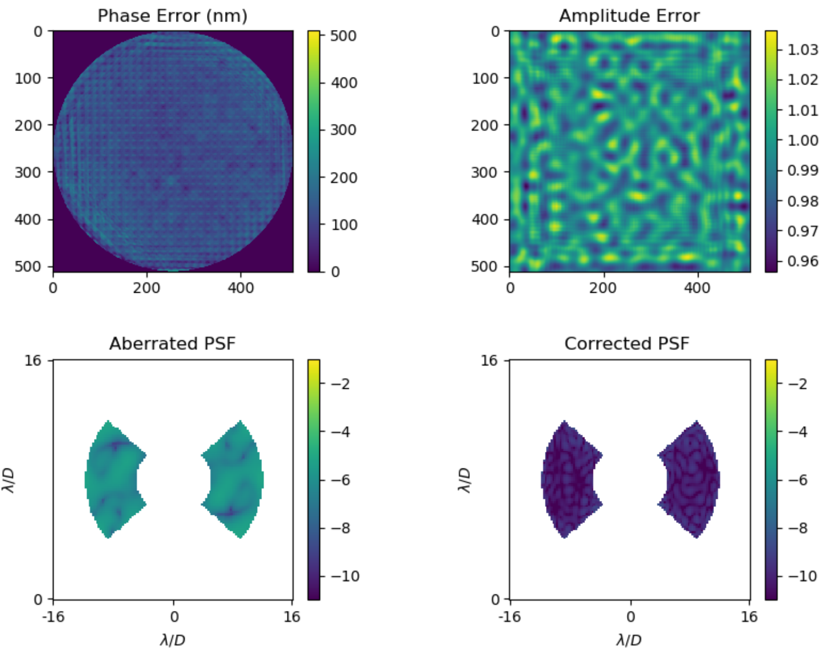
- DM voltage calculated by non-linear optimization
  - Python L-BFGS-B (quasi-Newton method)
  - Minimize cost function, provide the gradient
- Cost Function
  - Obtained by forward model of the system
- Gradient
  - Obtained by algorithmic differentiation* of each step of the forward model

** Jurling et al.*

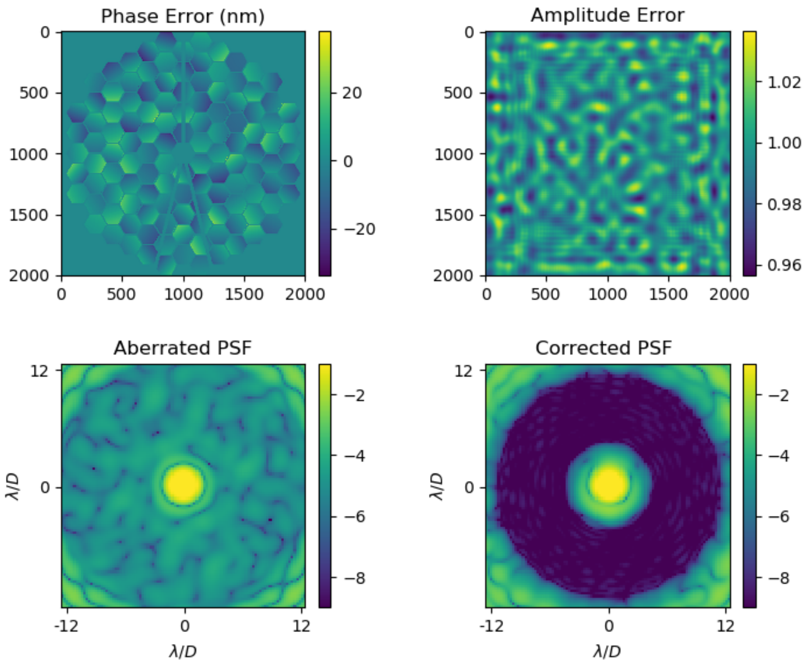
Simulation Results

- Three different coronagraphs
- Different combination of phase and amplitude error

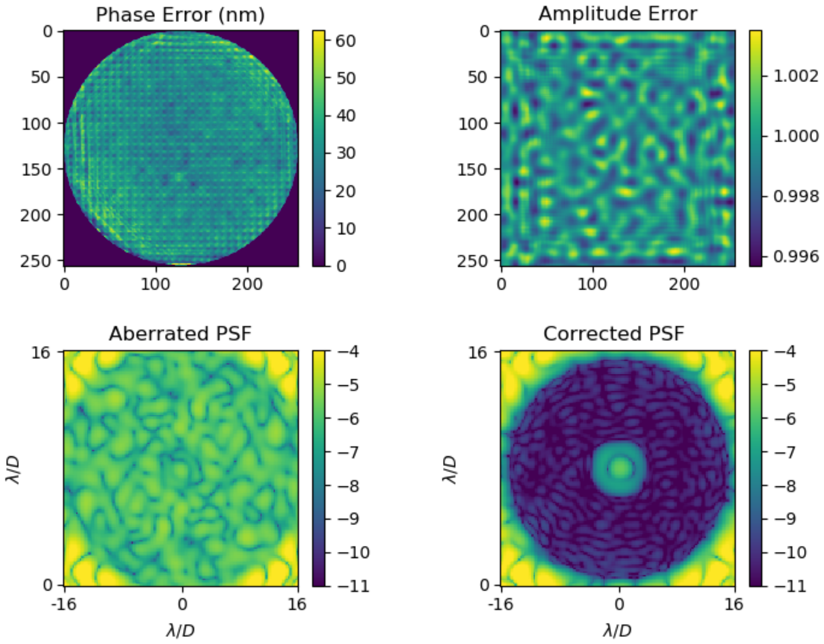
1) Ripple 3 SPC



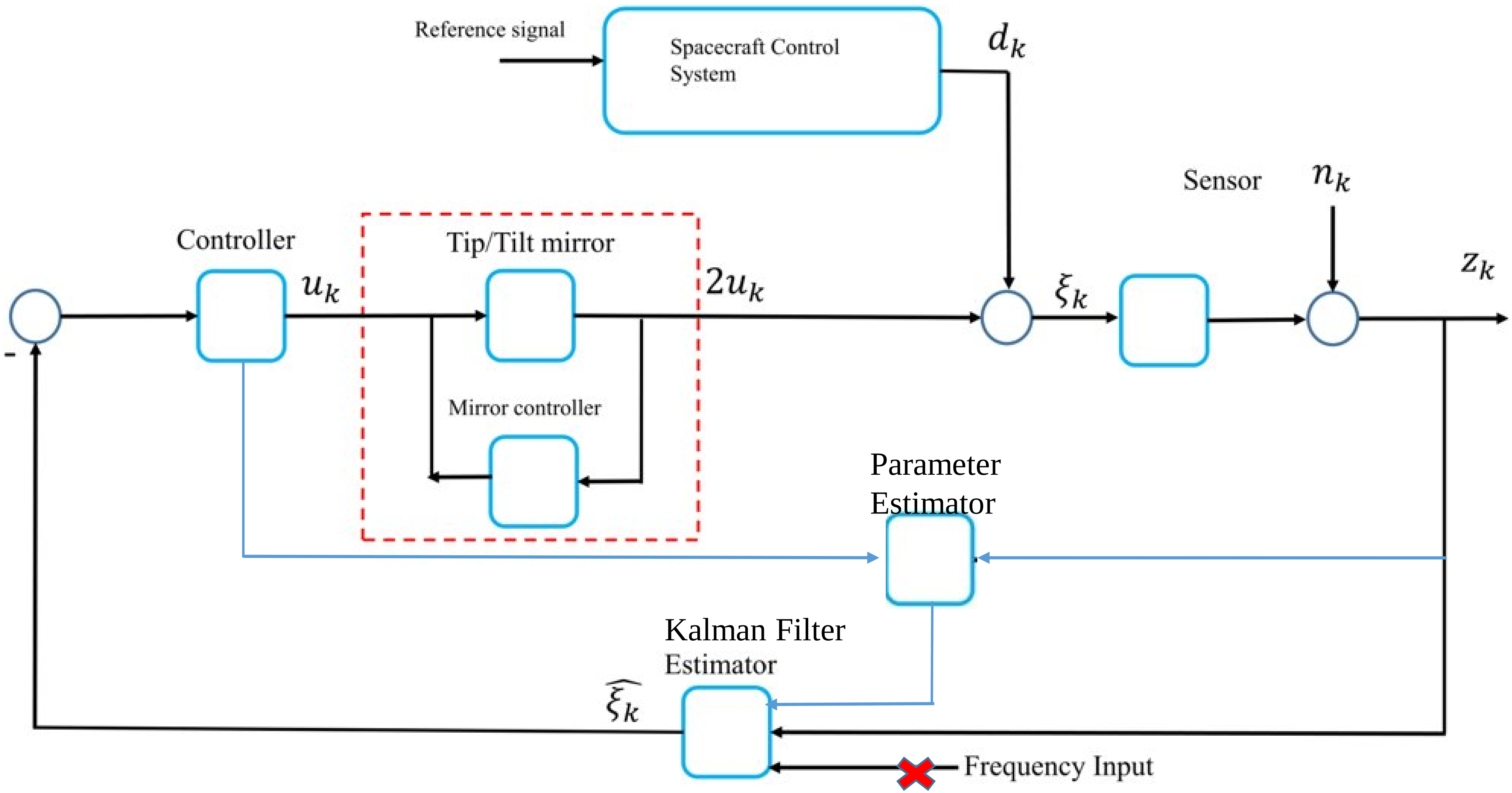
2) Lab coronagraph with segments errors



3) LUVOIR B Coronagraph



Adaptive Estimation of LOS

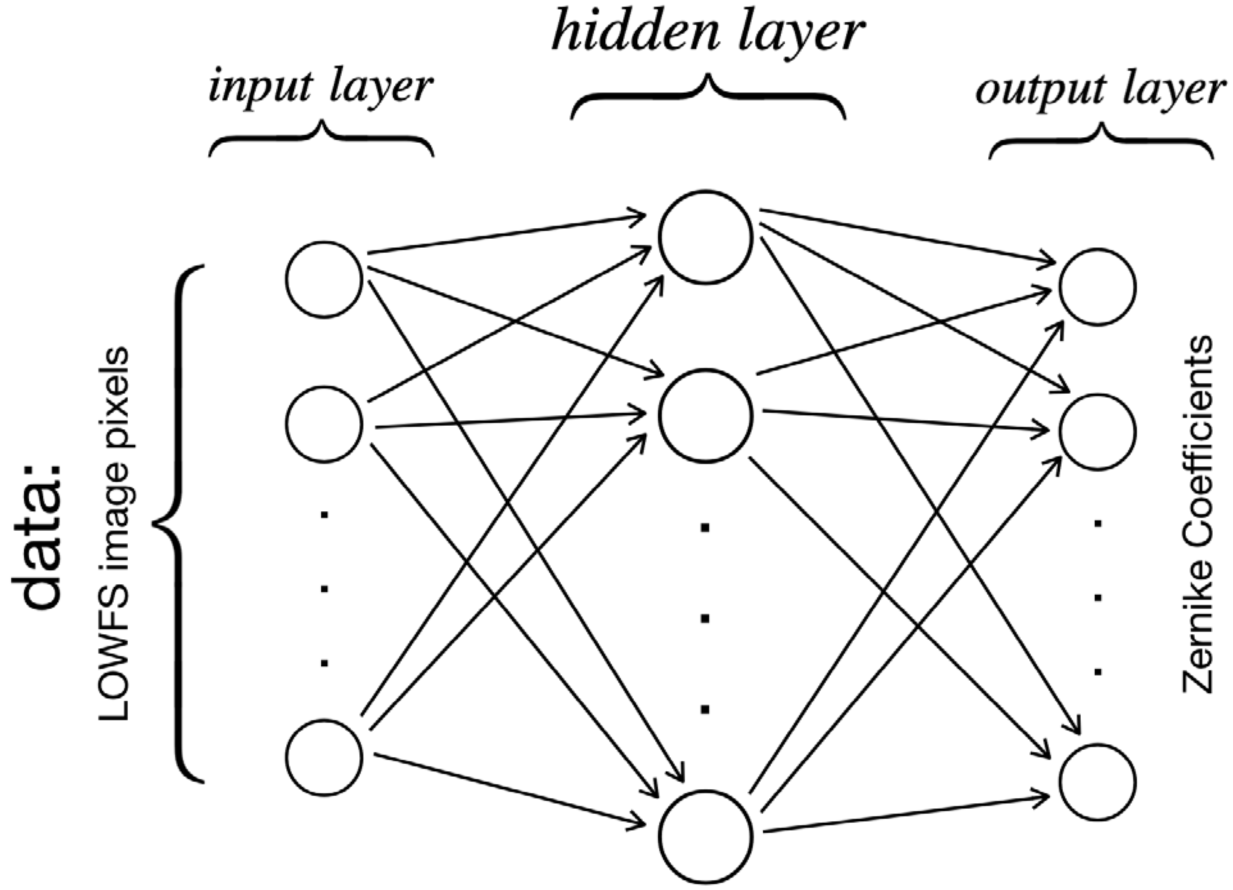


In Simulation, we have shown that residual after correction 0.4 mas.

Assumptions:

- Reaction wheel speed changing over time
- 2.4 telescope observing a star of magnitude 4.83

LOWFS - Machine Learning



Conclusion

- Making OAPs deformable is advantageous
  - Improvement control bandwidth
  - Better for packaging
  - Less risk and cost

- At NASA GSFC we are designing a multipurpose testbed
  - To test parabolic DM architecture
  - Different control algorithms

    -Non-linear dark hole digging, line-of-sight and LOWFS estimation and control