The Zernike wavefront sensor on the Decadal Survey Testbed

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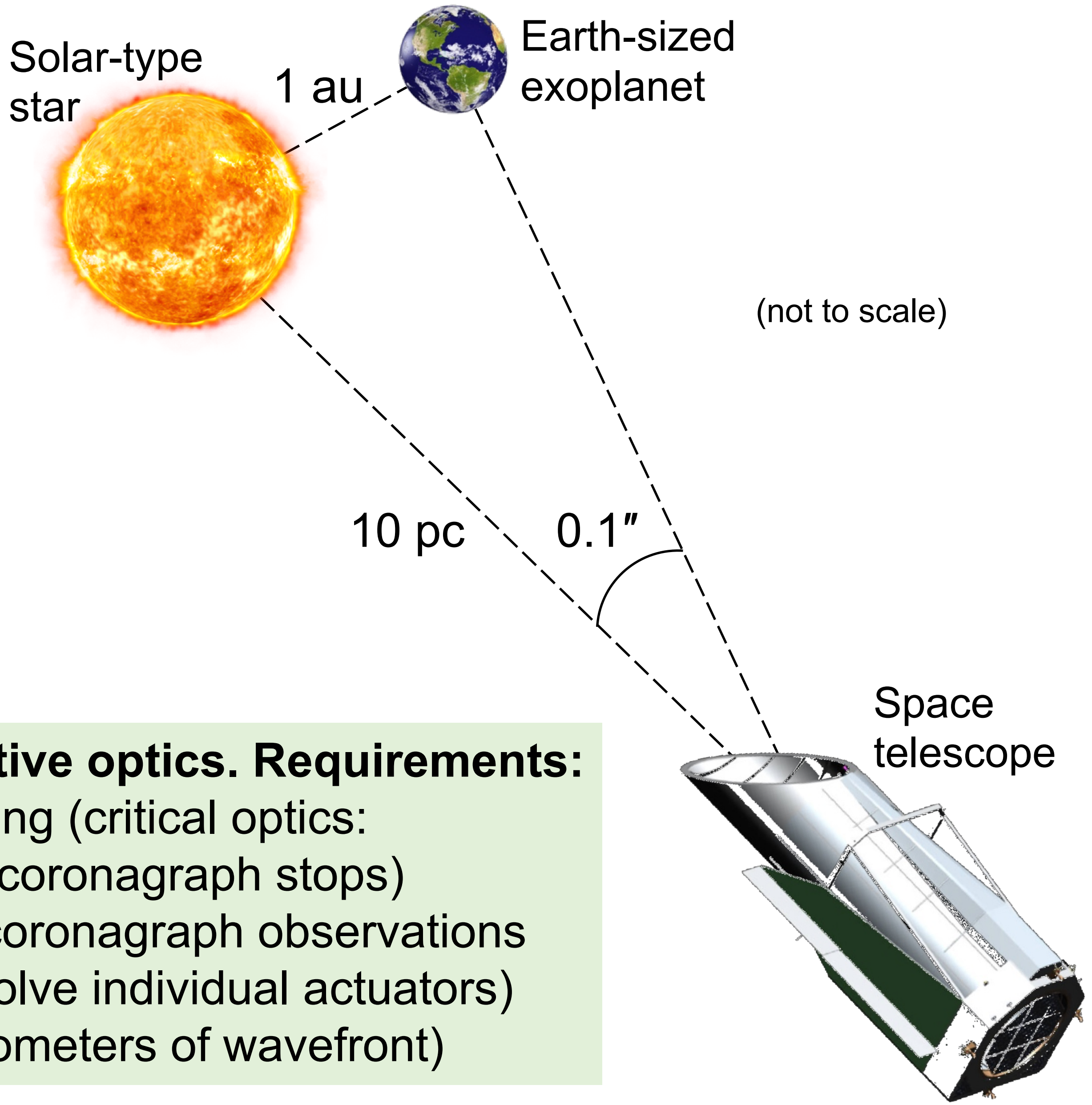
Requirements for HabEx/LUVOIR mission concepts

Science case: Imaging Earth-like exoplanets
1. Separations of interest: ~0.05″-0.5″
2. Raw contrast: ~10^{-10}
3. Integration times: ~10-1000+ hr

Wavefront stability requirements
1. Allowable wavefront changes (RMS):
    a. Lowest orders: ~100 pm
    b. Mid spatial freq: ~1-10 pm
2. Timescales: ~10-100 hr

Solution 1: Build an ultra-stable telescope and instrument that meets these requirements.

Solution 2: Use adaptive optics. Requirements:
1. Common path sensing (critical optics: everything up to the coronagraph stops)
2. Simultaneous with coronagraph observations
3. High resolution (resolve individual actuators)
4. High sensitivity (picometers of wavefront)



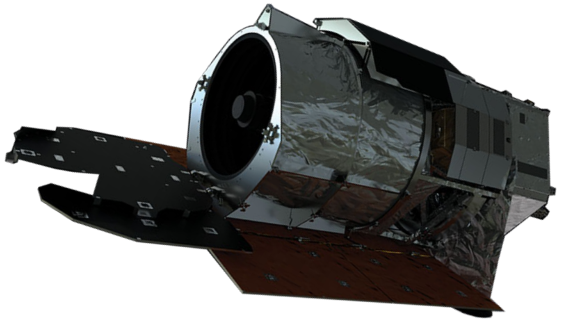
In situ wavefront sensors in high-contrast imagers

Adaptive optics requirements for HabEx/LUVOIR mission concepts:

1. Common path
2. Simultaneous
3. High resolution
4. High sensitivity

WFIRST CGI LOWFS (Shi+)

- Common path & simultaneous
- Low-order only



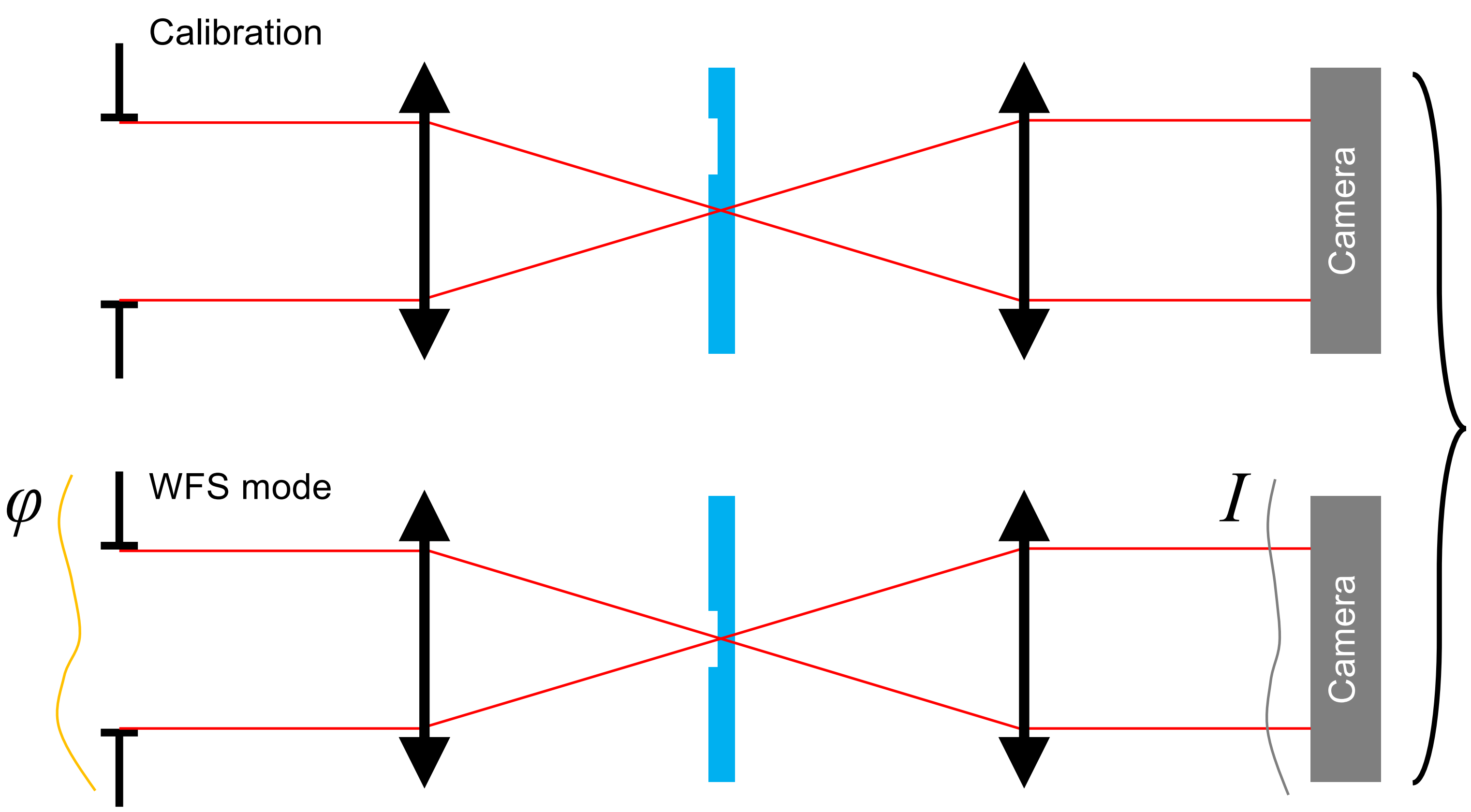
VLT/SPHERE/ZELDA (N'Diaye+)

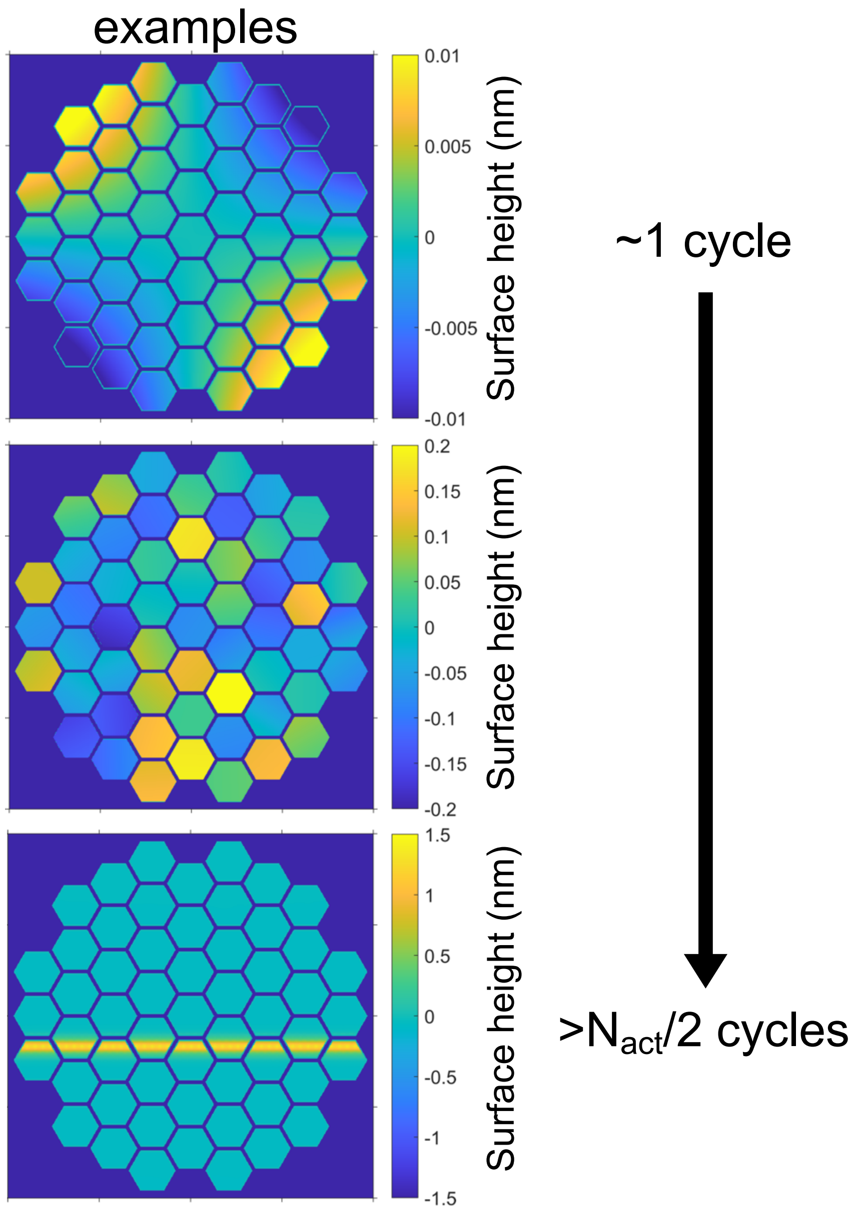
- Common path, high-res, sensitive by design
- Not simultaneous

Keck/KPIC/ZWFS (Wallace+)

- Simultaneous, high-res, sensitive by design
- No coronagraph

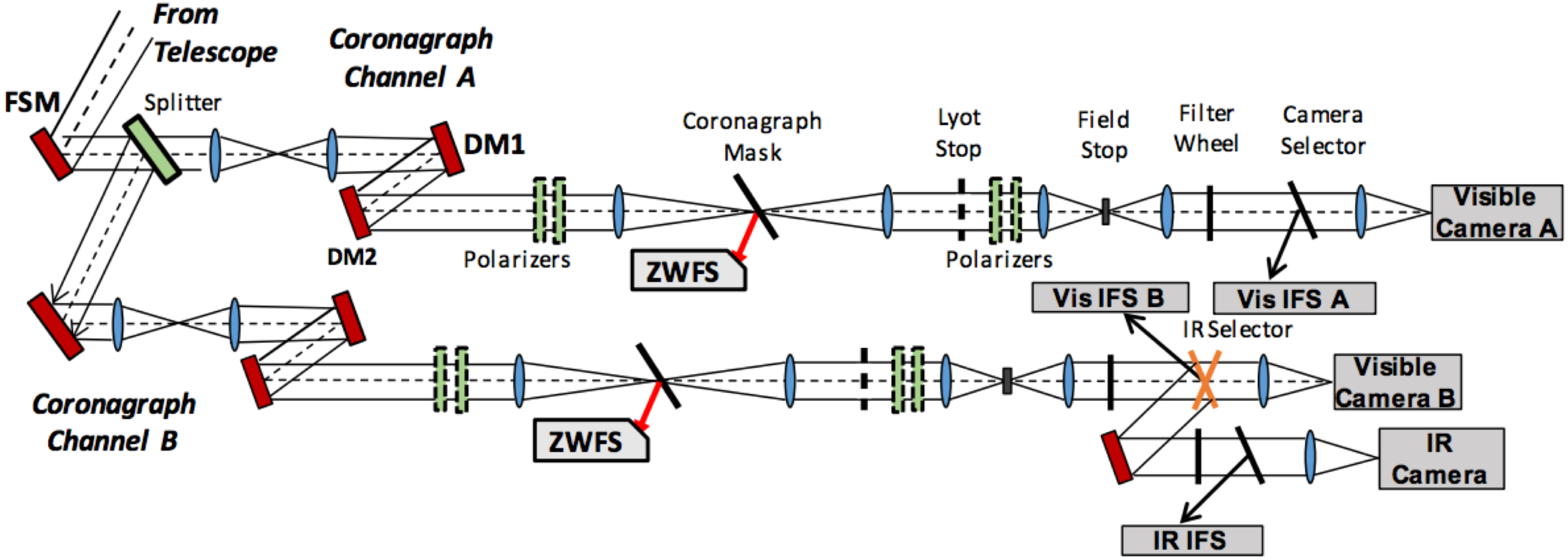
The Zernike wavefront sensor gives high sensitivity and high resolution





Makes use of Zernike's phase contrast method (F. Zernike 1934, 1955).
Also see Guyon 2006, Wallace+ 2011, N'Diaye+ 2013, Steeves+ submitted.

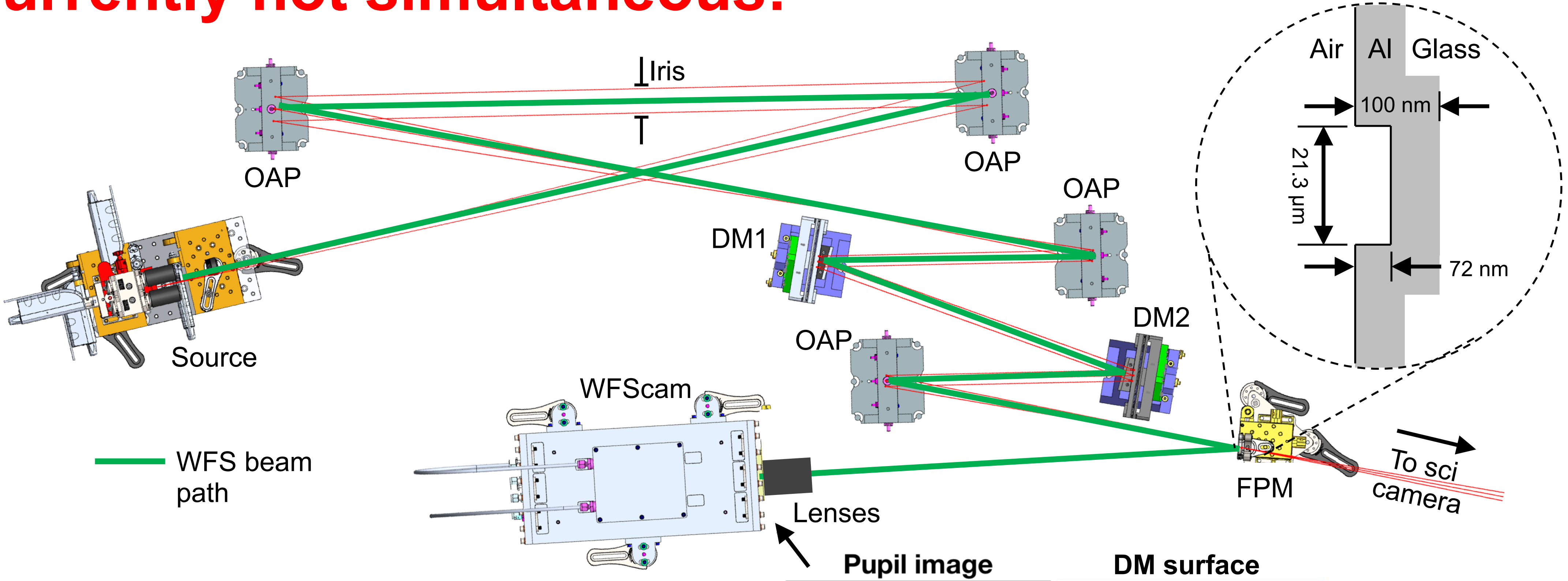
An out-of-band ZWFS is part of the HabEx mission concept



- Zernike wavefront sensor (ZWFS) gives **high-sensitivity** and **high-resolution**.
- Out-of-band ZWFS allows **simultaneous** operation with minimal impact to observations.
- Using a dichroic focal plane mask (or Lyot stop) makes it **common path**.

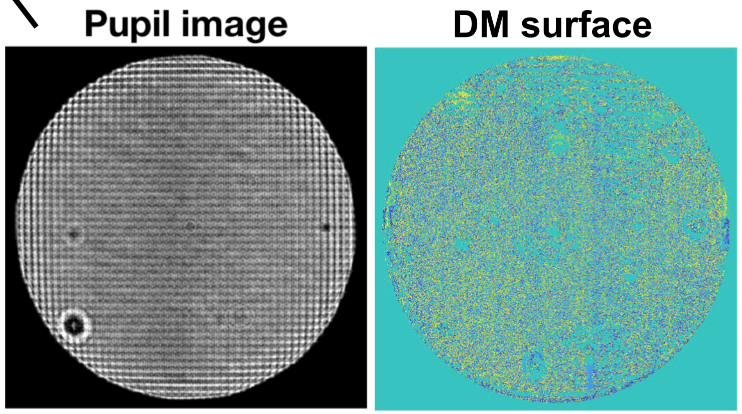
HabEx Report

The DST WFS implementation mimics HabEx, but it’s currently not simultaneous!



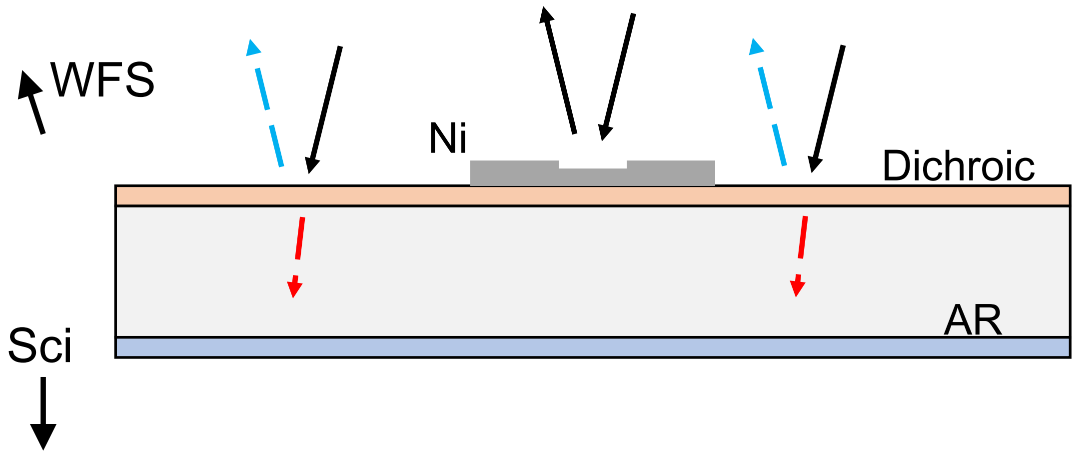
Main features:

- Two 50×50 BMC DMs
- Andor Neo sCMOS Camera
- DM1 is imaged onto the WFScam
- Image has ~660 pix across
- In vacuum



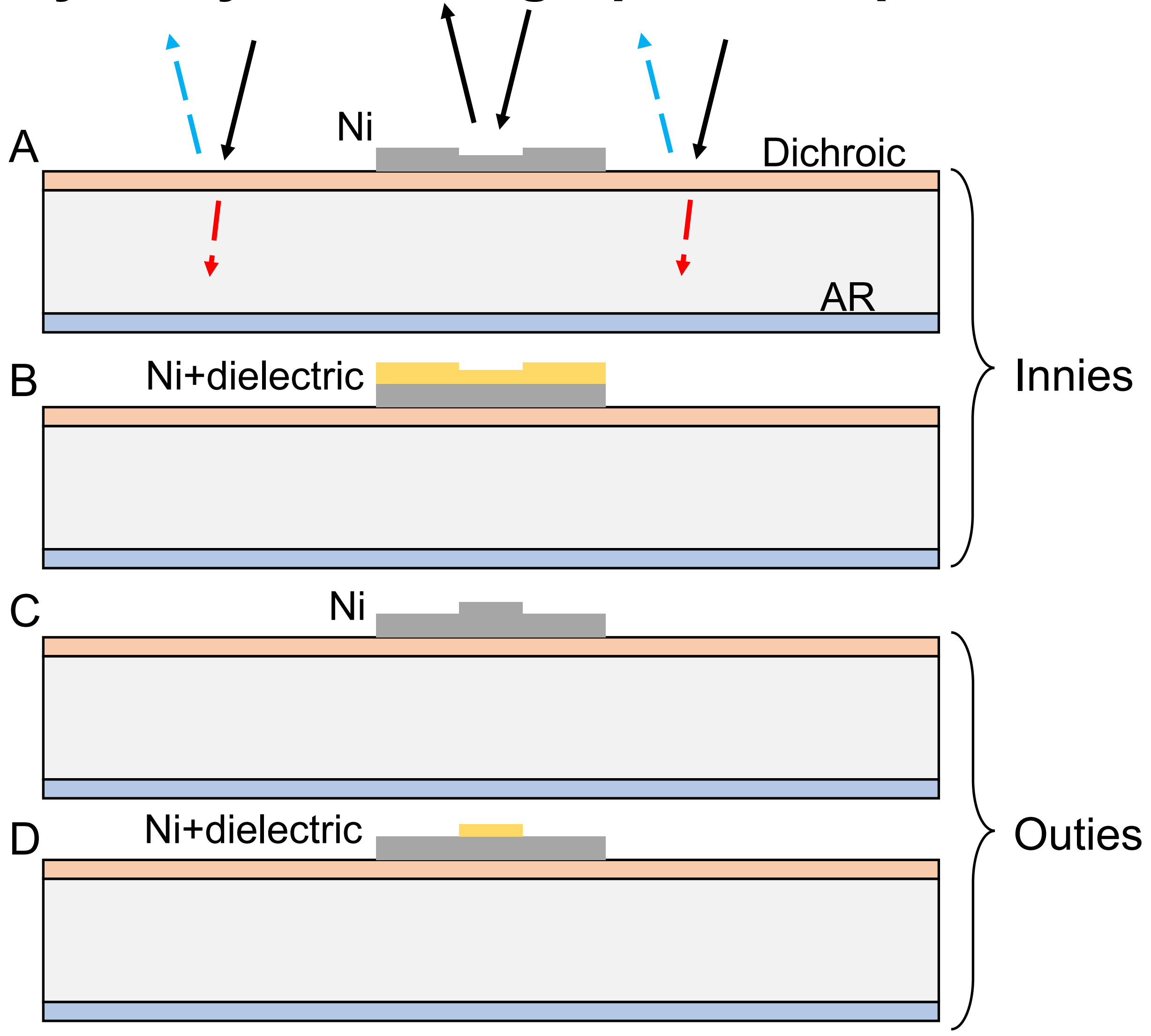
Raw ZWFS measurements when poking rows and columns on DM1

How to make it simultaneous? FPM coatings and dimples

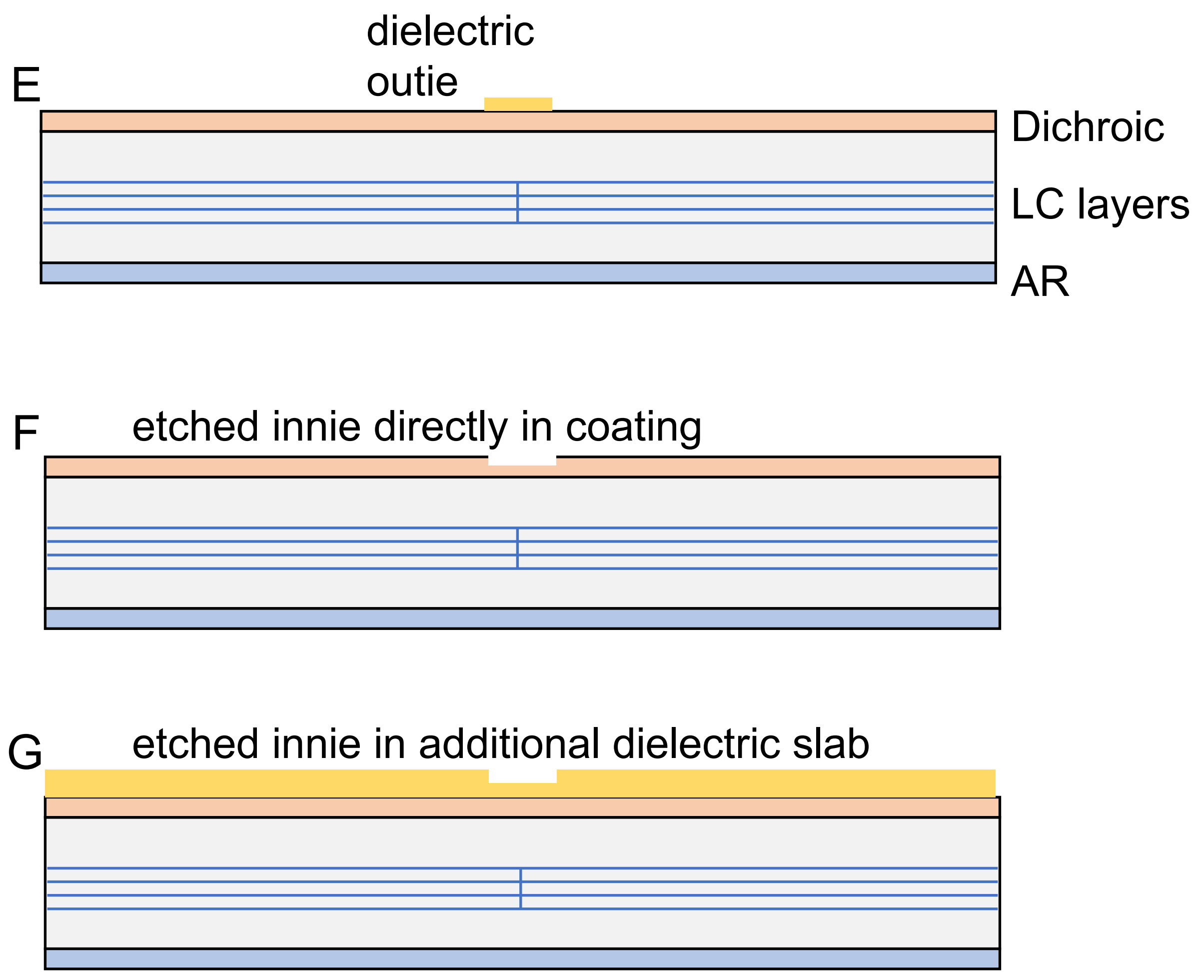


How to make it simultaneous? FPM coatings and dimples

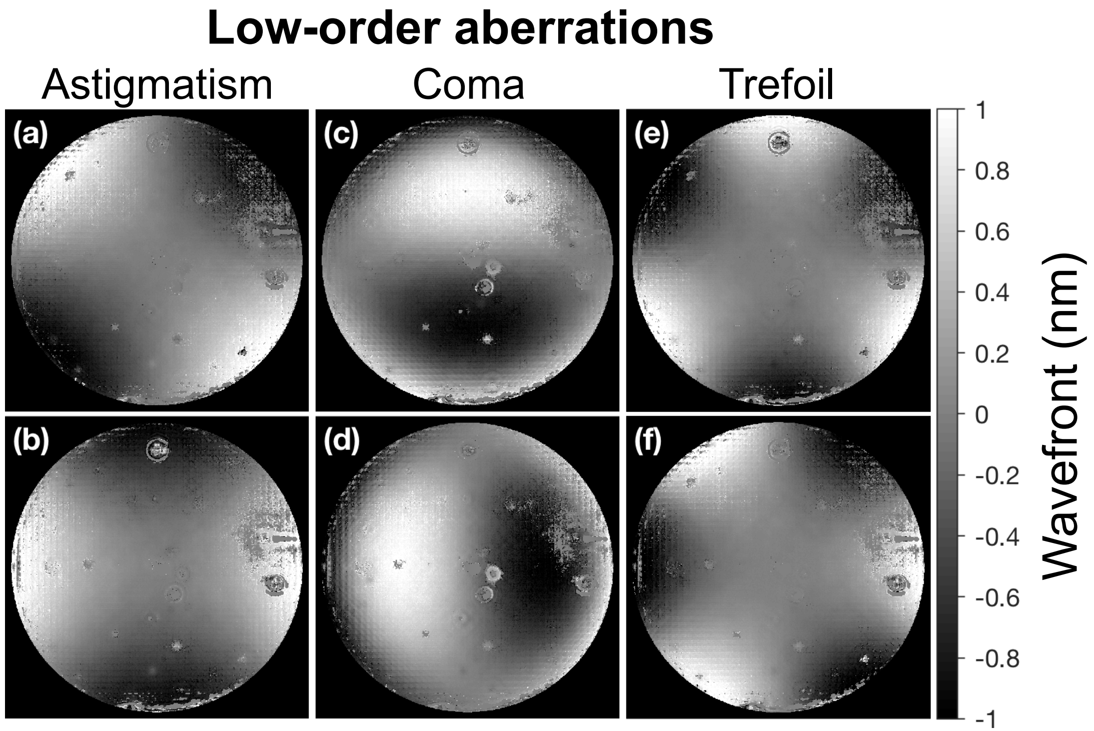
Lyot-style coronagraph concepts

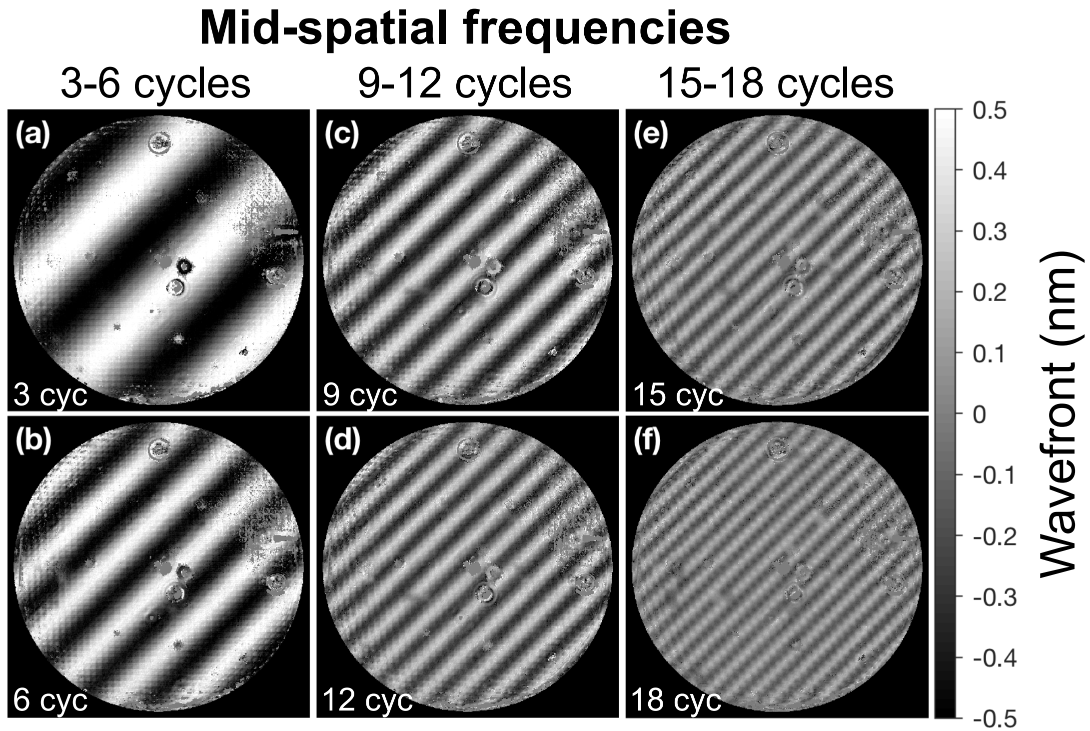


Vortex-style coronagraph concepts



The reflective WFS responds as expected

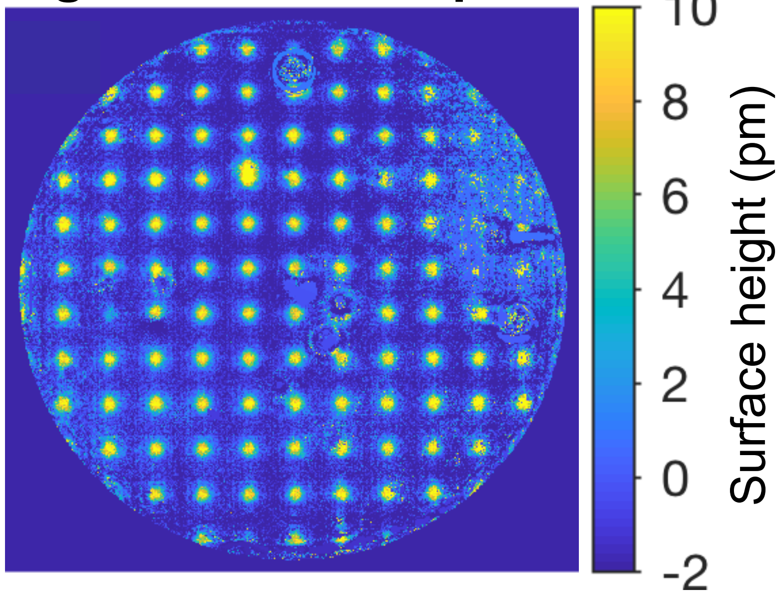




We injected (*left*) Zernike polynomials and (*right*) sine waves in the DM voltage commands to demonstrate sensitivity to a large range of relevant spatial frequencies.

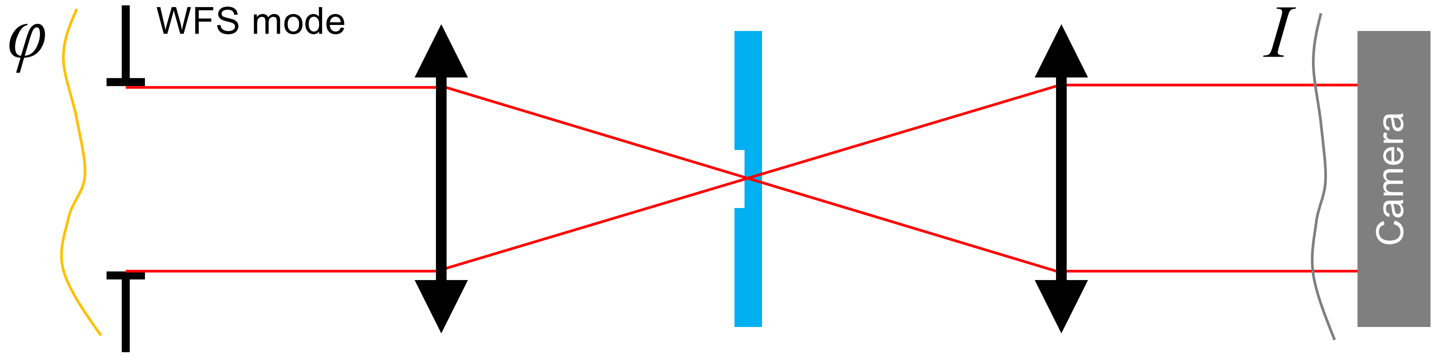
Picometer-level sensitivity is feasible, but time consuming!

Single-bit actuator pokes



- The least significant bit corresponds to a motion of 11 pm at the peak of isolated actuators.
- Noise in surface height difference measurement is <1 pm.
- Integration time is 10,000 sec (2.8 hr) per DM state.
  - Discrete integration time is 10 ms per frame.
  - We switched between the two DM states 1,000 times taking 10,000 frames at a time.
  - This experiment combines *1 million* WFS frames per DM state.

Building a detailed error budget



For "small" phase changes:

$$\Delta\phi = \frac{\Delta I}{2Ab\beta}$$

- ΔI: Intensity difference
- A: Pupil amplitude estimate
- b: Reference wave estimate
- β: Interference function

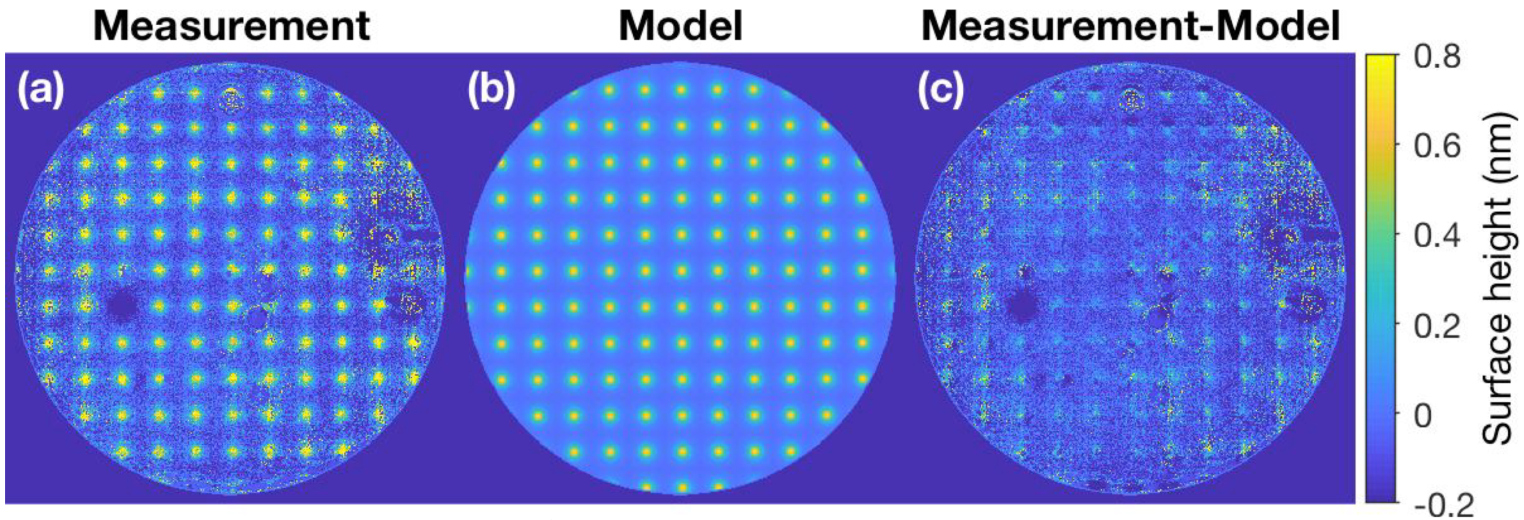
Important terms in the error budget:

- Random noise (detector, photon-counting)
- Calibration error & systematics:
  - Ref wave: dimple diameter and F#
  - Source spectrum and spectral responsivity
  - Dimple depth/phase shift, $\beta \propto \sin(\theta)$
  - Nominal wavefront, Φ, $\beta \propto \cos(\Phi)$
  - Angle of incidence
  - Dynamic wavefront error / Jitter
  - Pupil shear

Ruane+, in prep

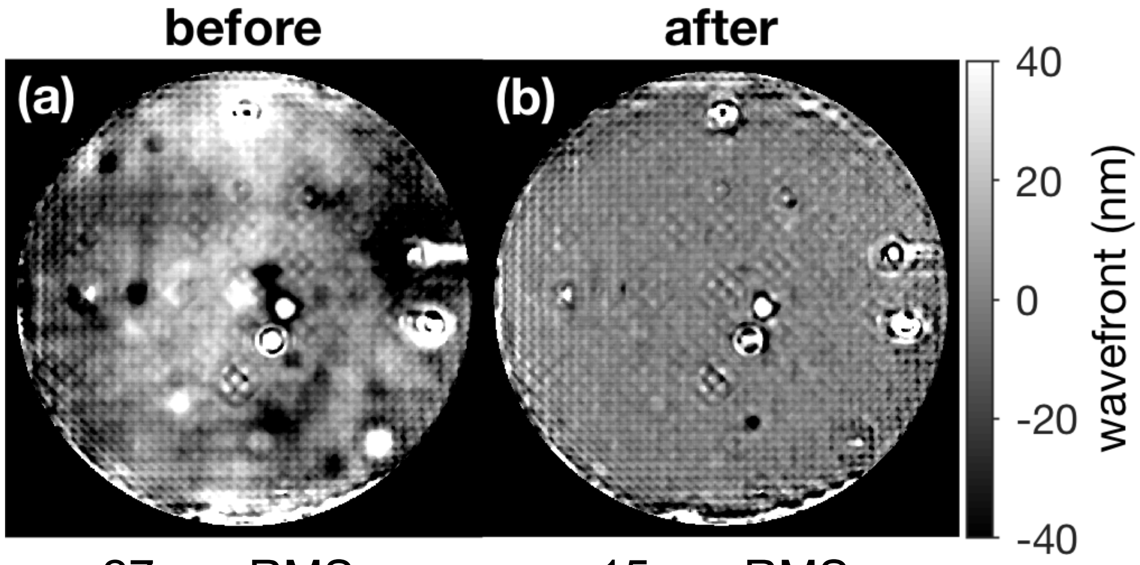
Demonstrating closed-loop control

Step 1:
Build DM model



DM model fit using FALCO: translation, rotation, scaling, gains.

Step 2:
Flatten the wavefront

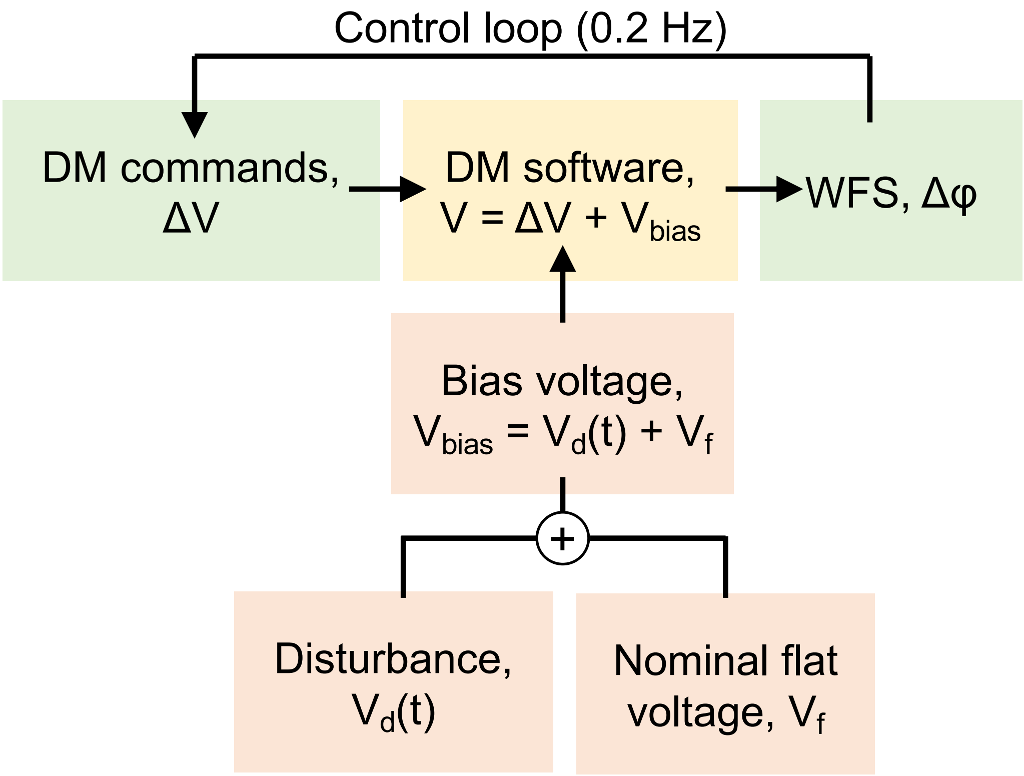


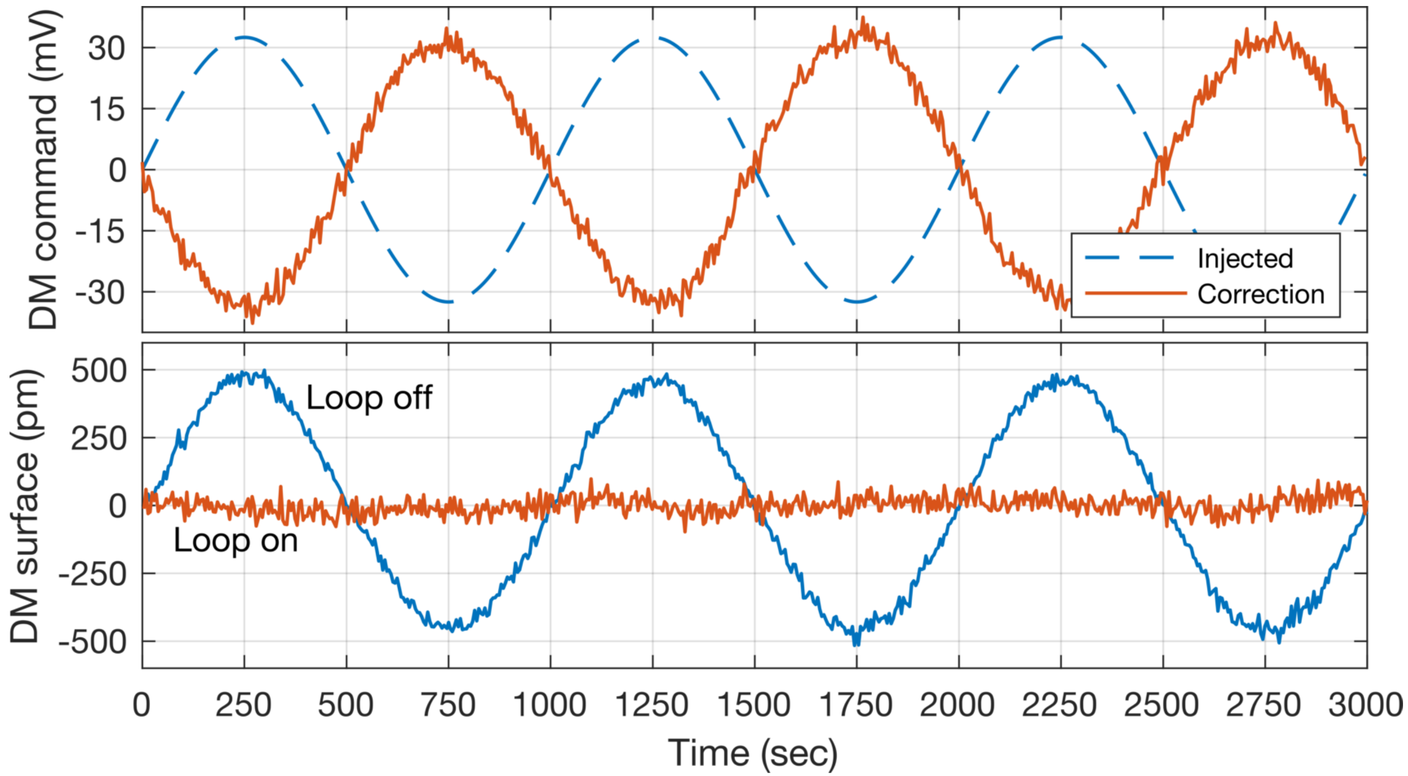
27 nm RMS   15 nm RMS

Ruane+, in prep

Demonstrating closed-loop control

Step 3: Close the loop to "lock" the wavefront.

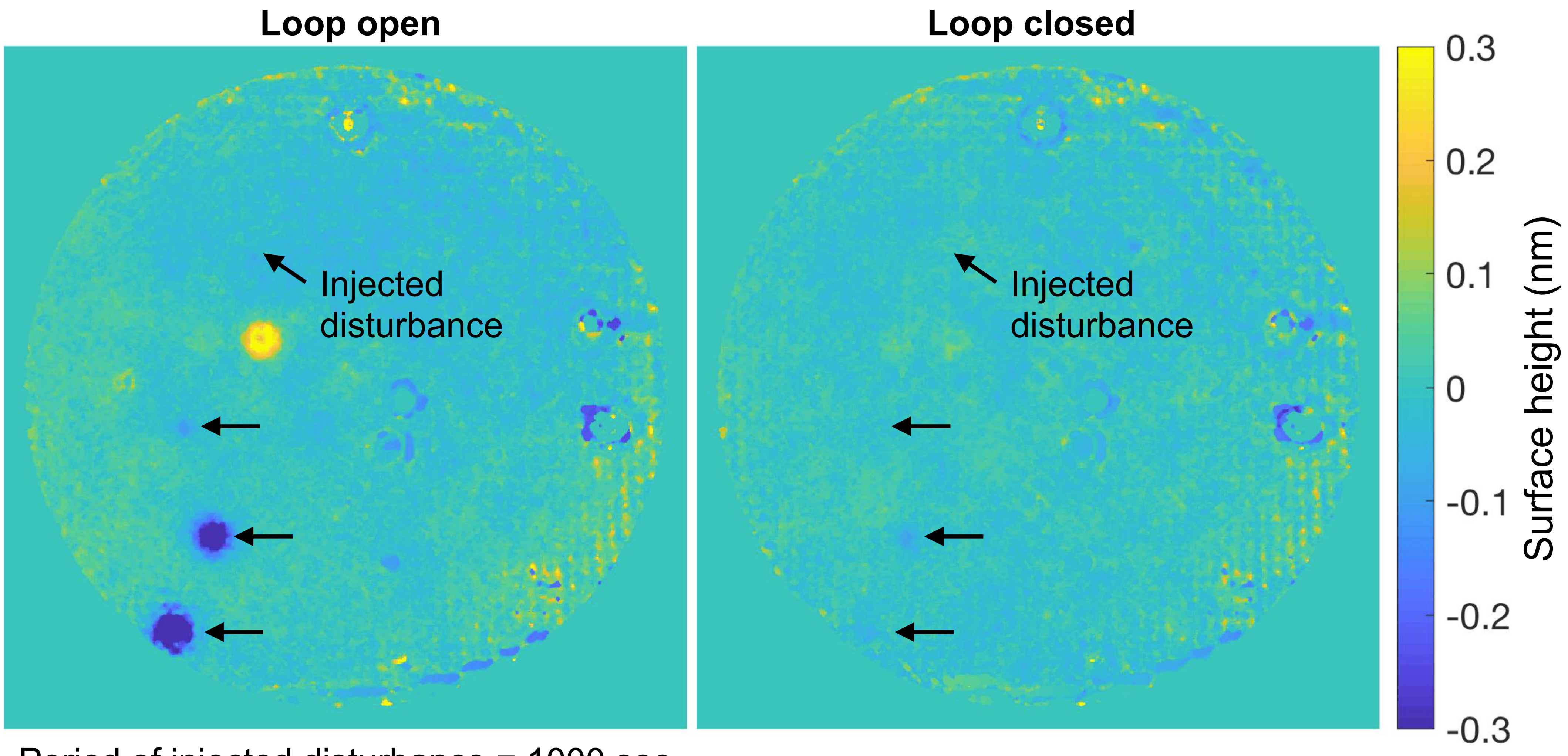




Period of injected sine wave = 1000 sec, K = 0.8, 0.2 Hz loop, t_{int} = 1 sec, 30 pm RMS residual

Ruane+, in prep

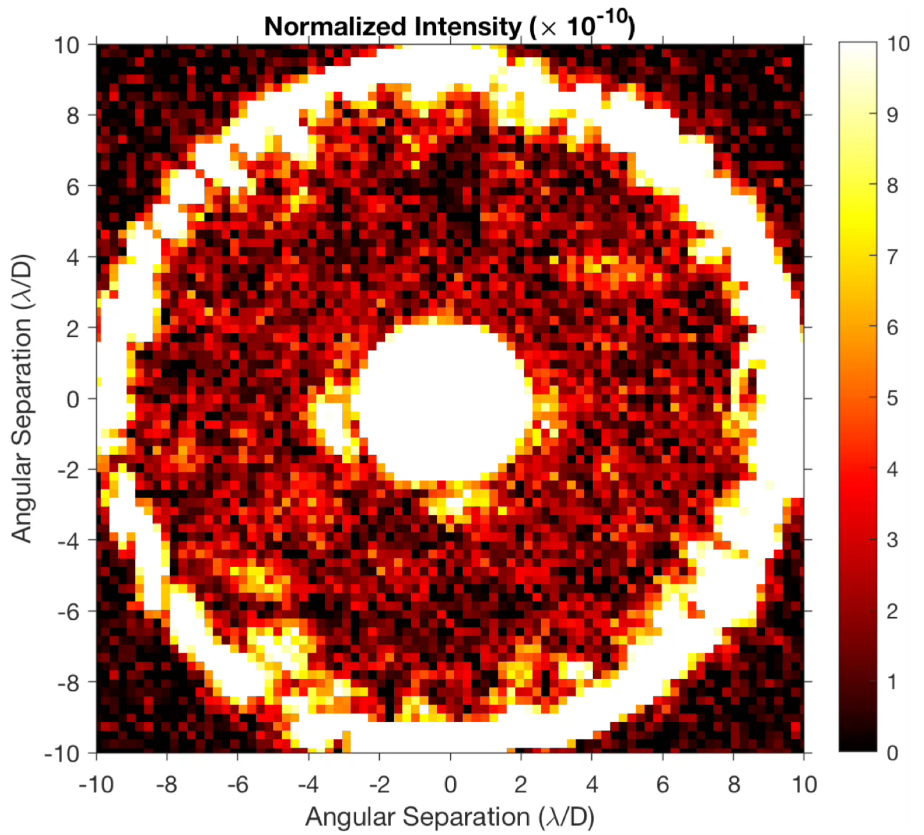
Closed-loop control of a "noisy" DM



Period of injected disturbance = 1000 sec,
0.2 Hz loop, t_{int} = 1 sec, duration = 3000 sec = 50 min
Playback rate = 10 fps = 50x real time

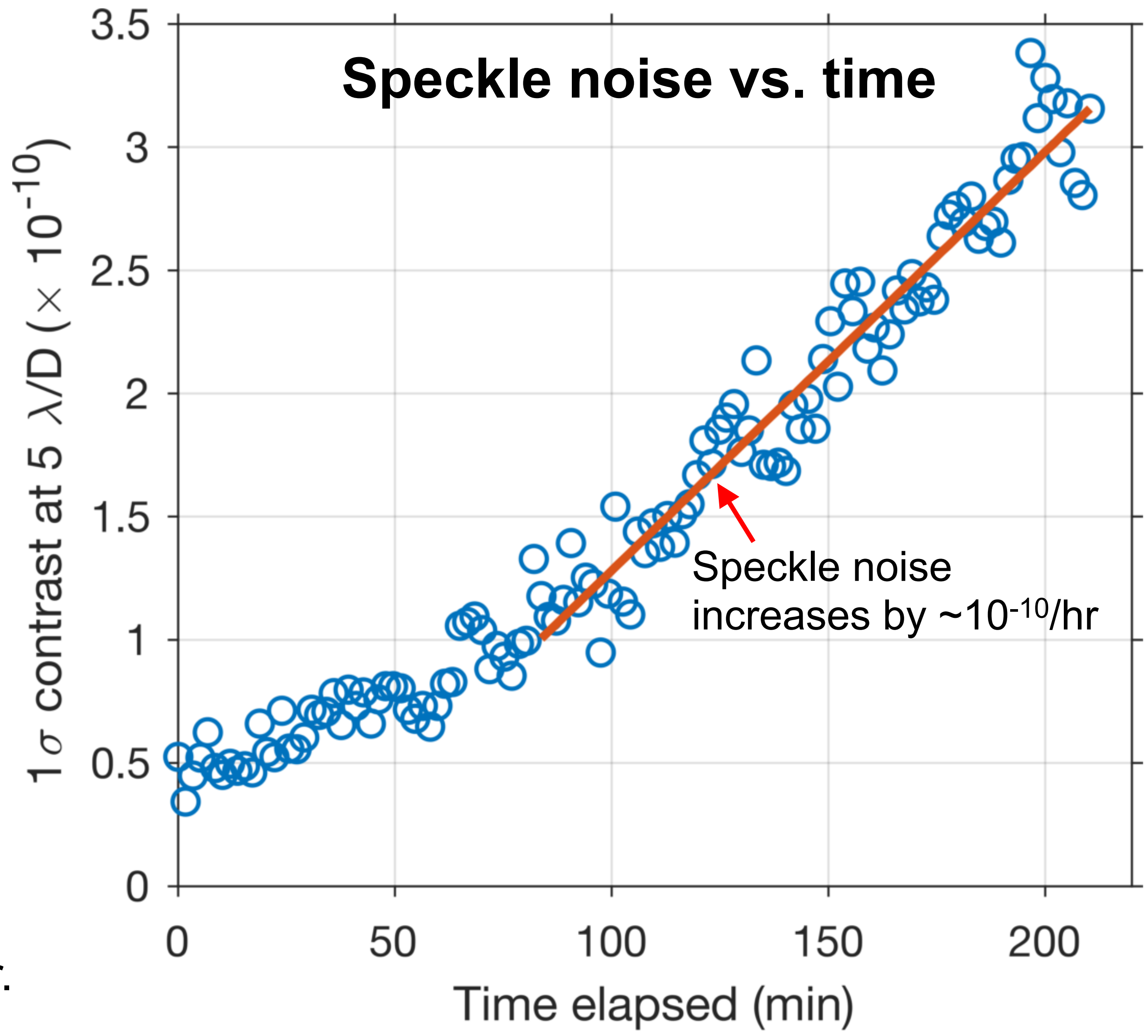
Correction with 1 hr update rate will help stabilize speckles

"Set and forget" test



(raw data, 1000x speed)

- Monochromatic light at λ = 543 nm.
- Continuous 100 sec exposures for 3.5 hr.



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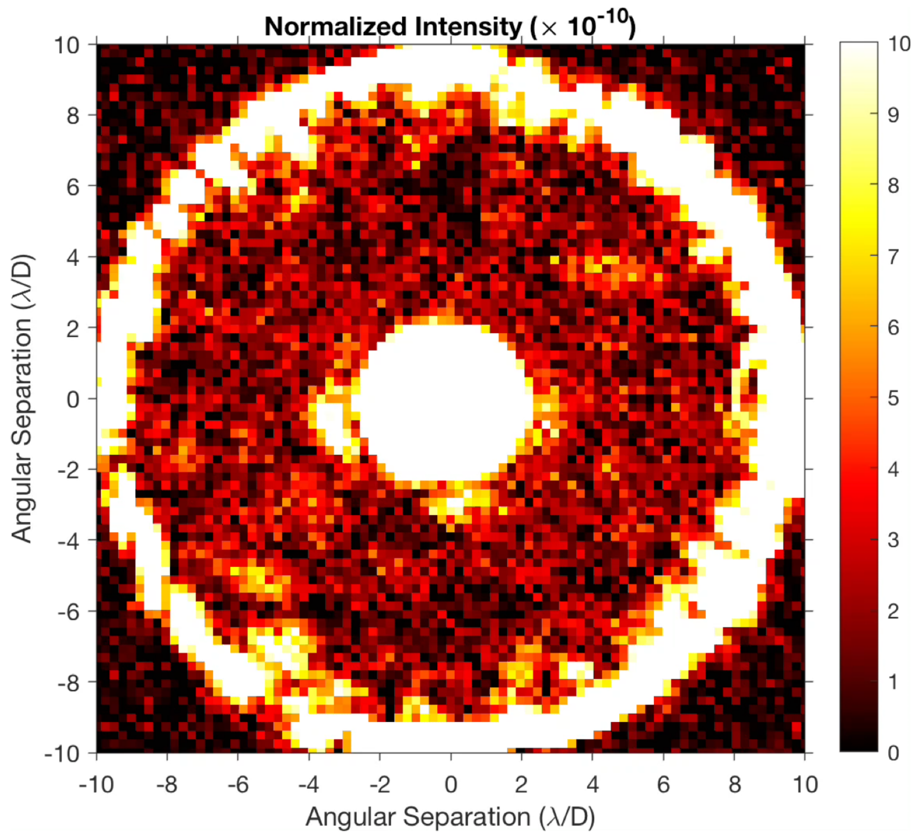

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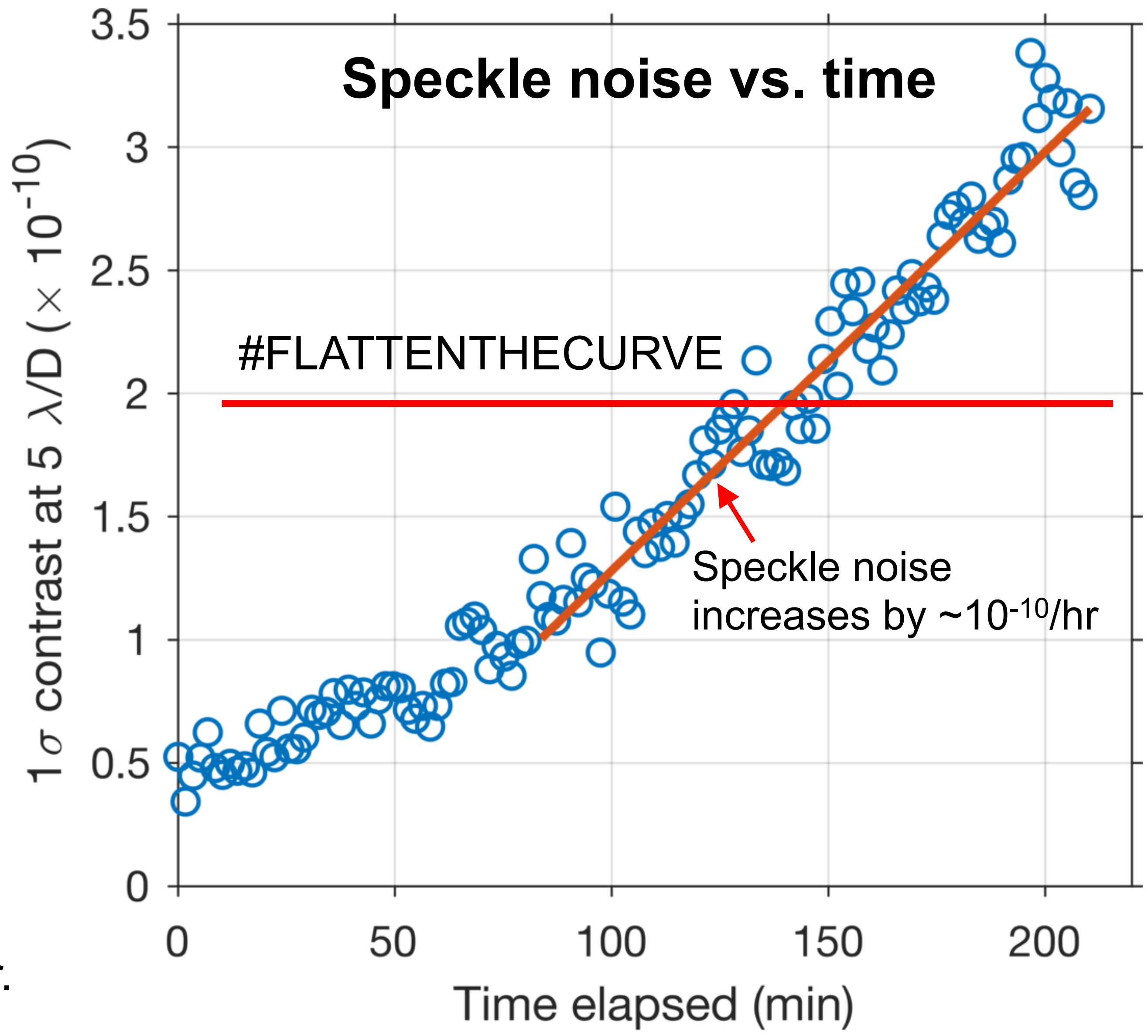

Take away points

- We commissioned the hardware needed for simultaneous, common-path, low- and mid-spatial frequency wavefront sensing on DST.
- The WFS beam path, camera, reflective masks are part of the DST facility hardware are available for use by PIs.
- Non-simultaneous, reflective Zernike WFS on DST achieved picometer sensitivity and closed-loop control.
- DST is now equipped for system-level coronagraph demonstrations using pupil plane wavefront sensing techniques that are simultaneous and common path, in addition to “conventional” focal plane wavefront sensing.