Coronagraph Testbed Challenges

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1a. DST commissioning

NASA's High Contrast Imaging Testbed (HCIT) facility

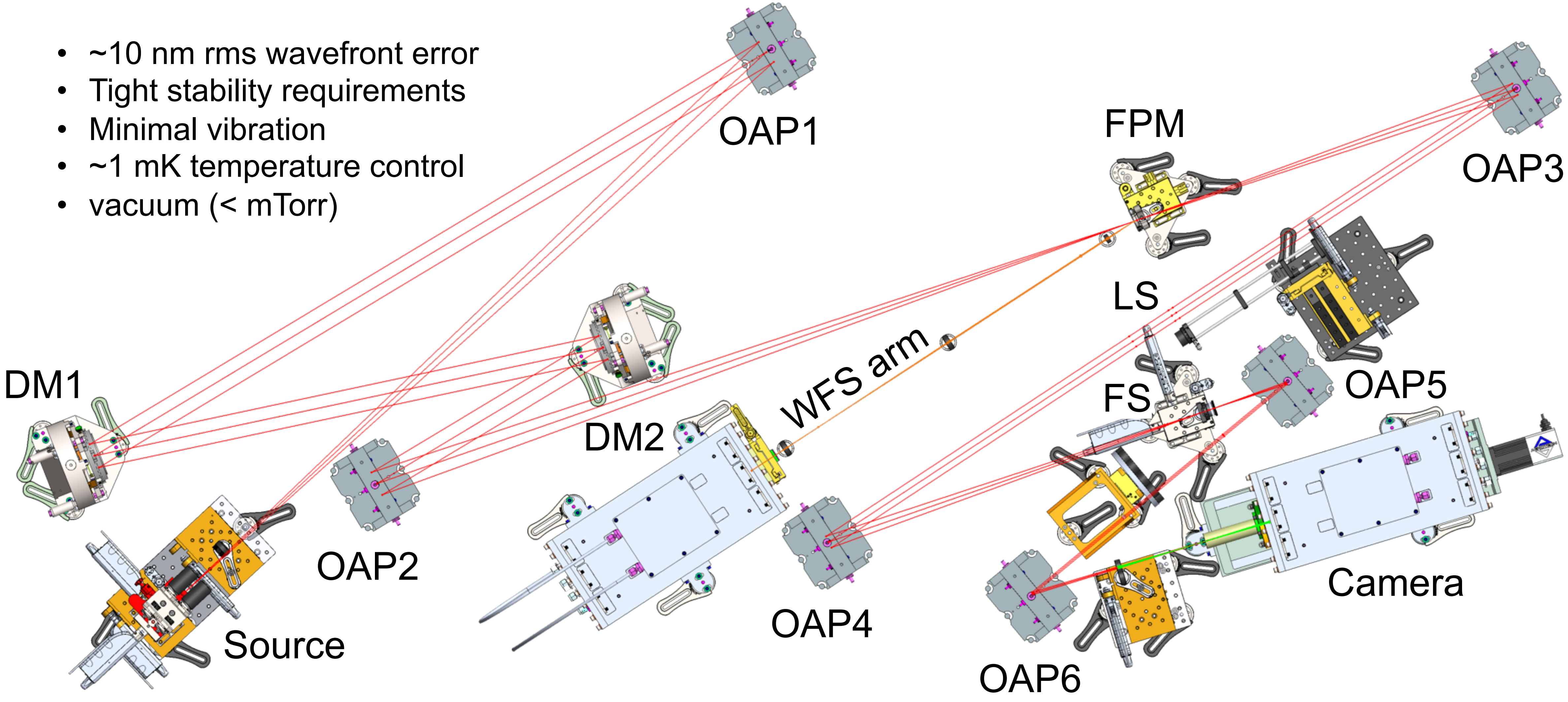
- The "twin" DSTs are ultra-stable testbeds for coronagraph instruments capable of achieving performance commensurate with direct imaging of Earth-sized exoplanets in the HZ of Solar-type stars.
- DST-1 achieved our record contrast: ~4e-10 in a 10% spectral bandwidth.
- DST-2 recently commissioned. Results to be presented at SPIE.

Patterson et al., Proc. SPIE 111171U (2019)
Seo et al., Proc. SPIE 111171V (2019)
Meeker et al., Proc. SPIE 118230Y (2021)
Noyes et al., Proc SPIE, in prep. (2023)

DST = Decadal Survey Testbed

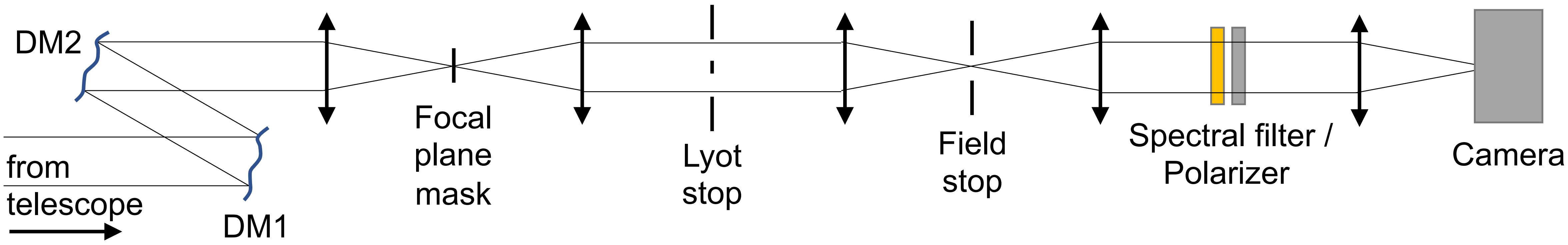
The Decadal Survey Testbed design

- ~10 nm rms wavefront error
- Tight stability requirements
- Minimal vibration
- ~1 mK temperature control
- vacuum (< mTorr)

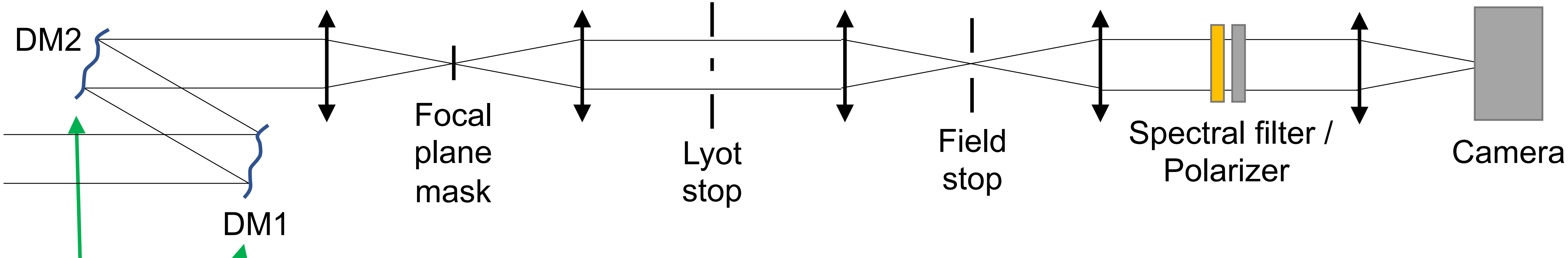


Patterson et al., Proc. SPIE 111171U (2019)

A simplified layout …

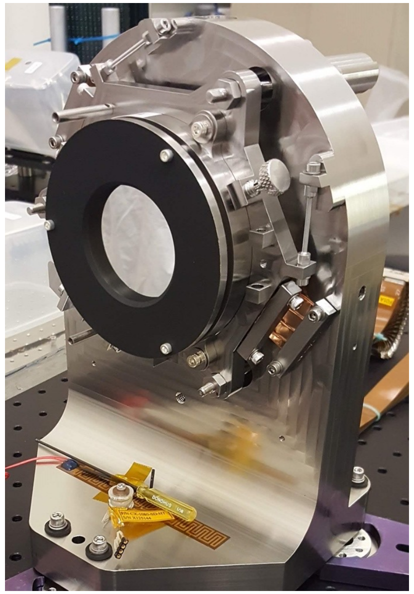


HCIT primarily uses two DM technologies



Deformable mirror set #1

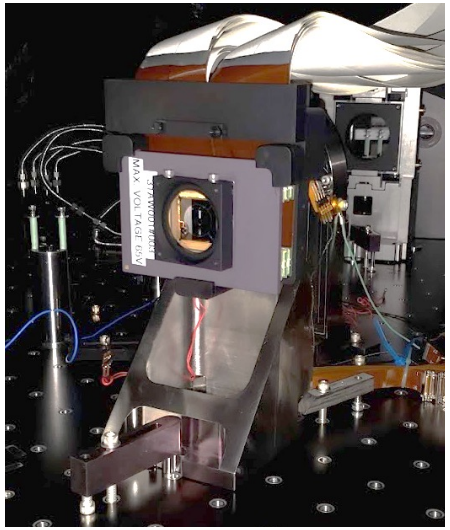
- Northrup Grumman AOA Xinetics (AOX) electrostrictive
- Lead magnesium niobate (PMN) electroceramic actuators
- 48 actuators across
- 1 mm pitch



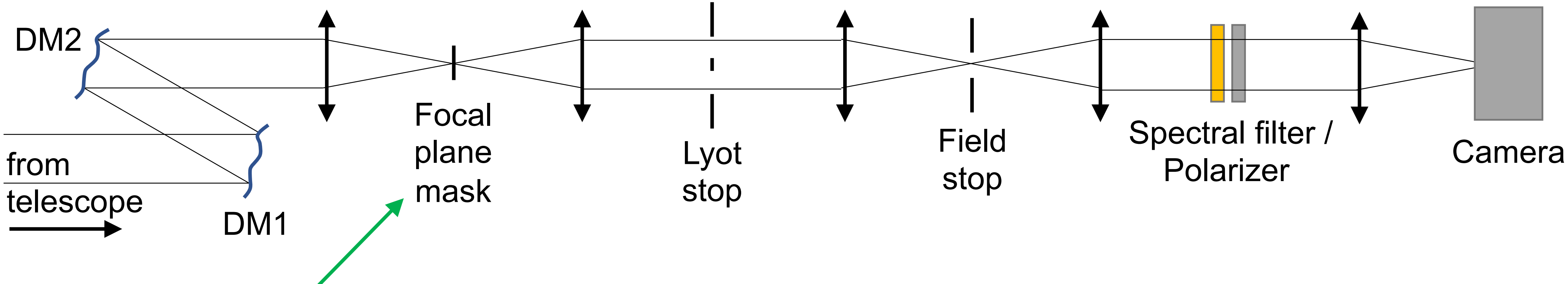
-OR-

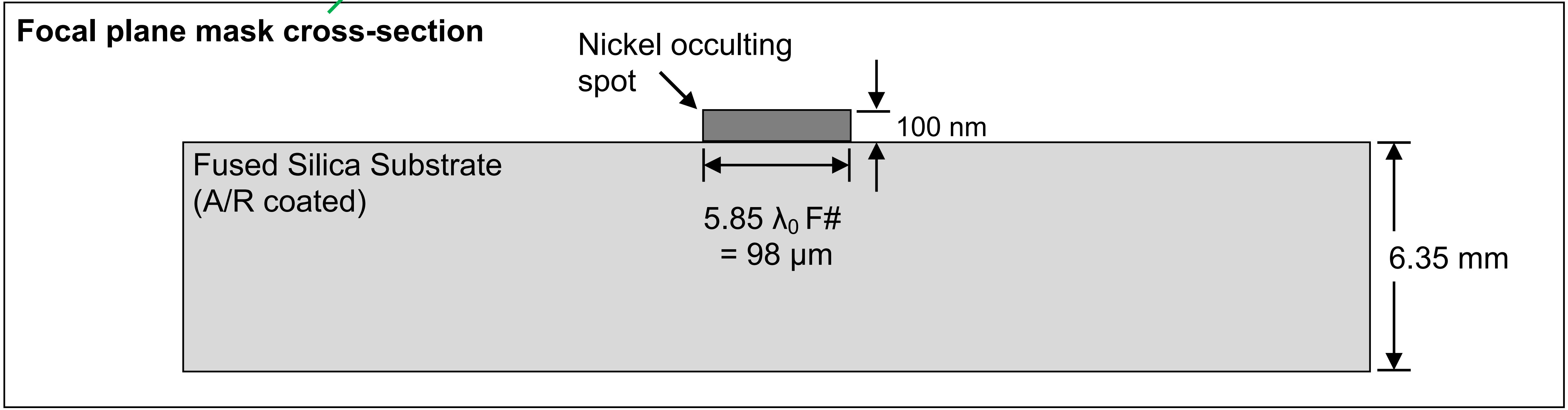
Deformable mirror set #2

- Boston Micromachines Co (BMC) MEMS
- Metallic coating on Silicon membrane
- Electrostatic actuators
- 50 actuators across
- 0.4 mm pitch



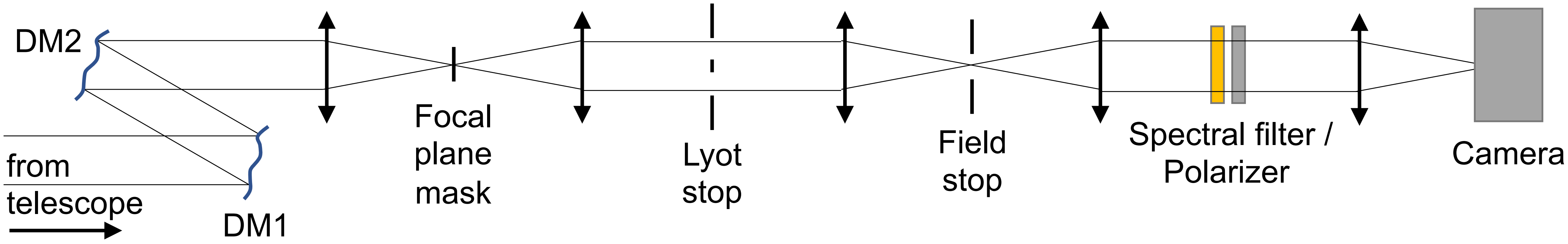
Focal plane mask is Nickel-on-glass occulter

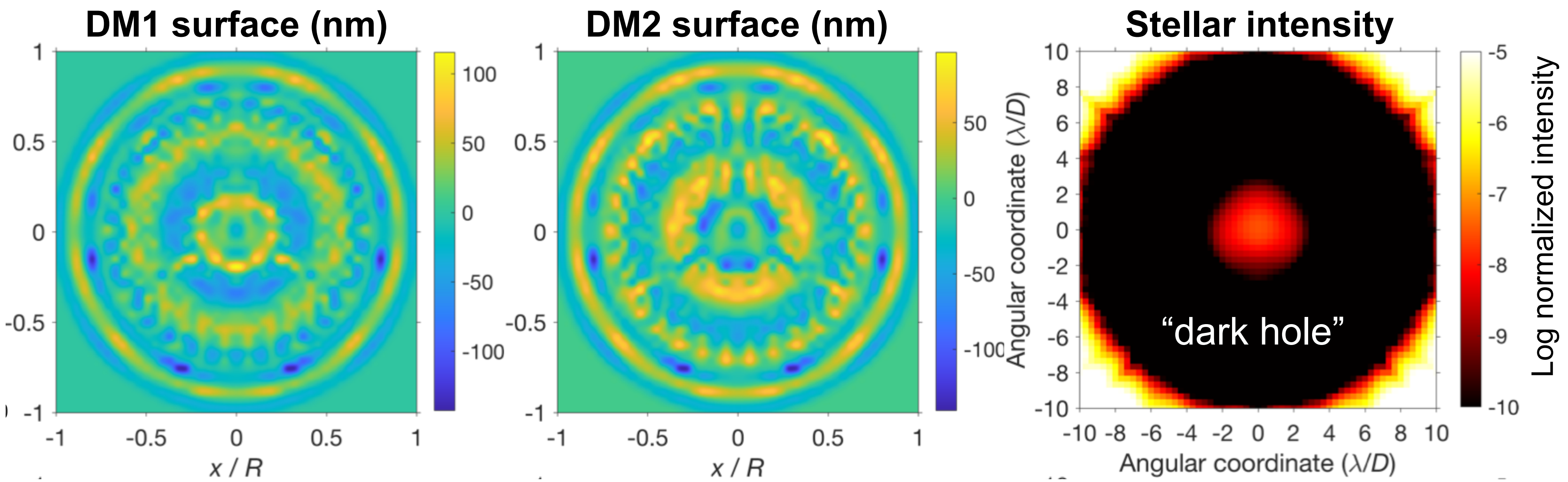




Seo et al., Proc. SPIE 111171V (2019)

DM-apodized Lyot coronagraph simulation

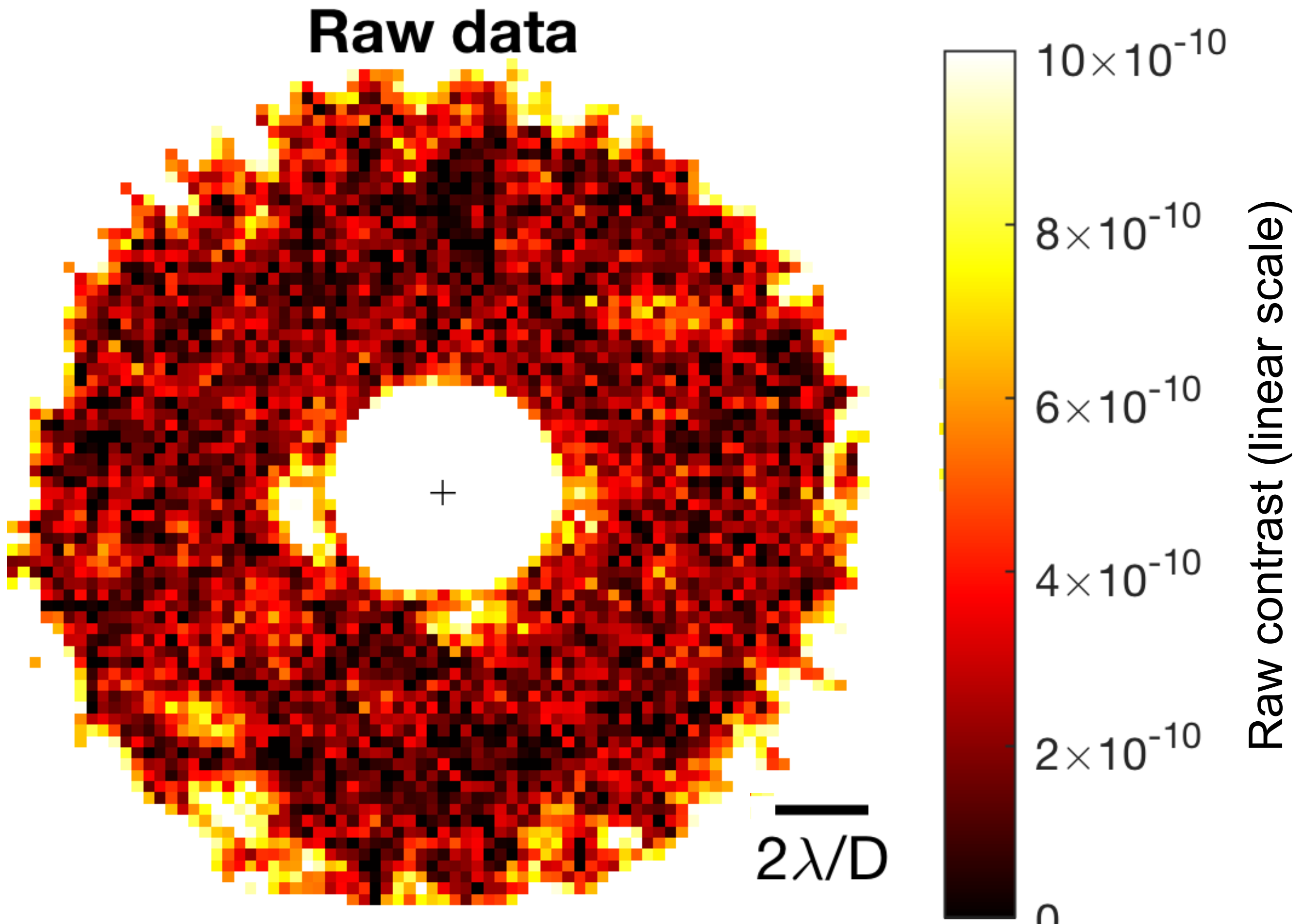




Trauger et al., Proc. SPIE 84424Q (2012); Riggs et al., Proc. SPIE 106982V (2018)

Monochromatic dark holes reach **2×10^{-10}** mean contrast

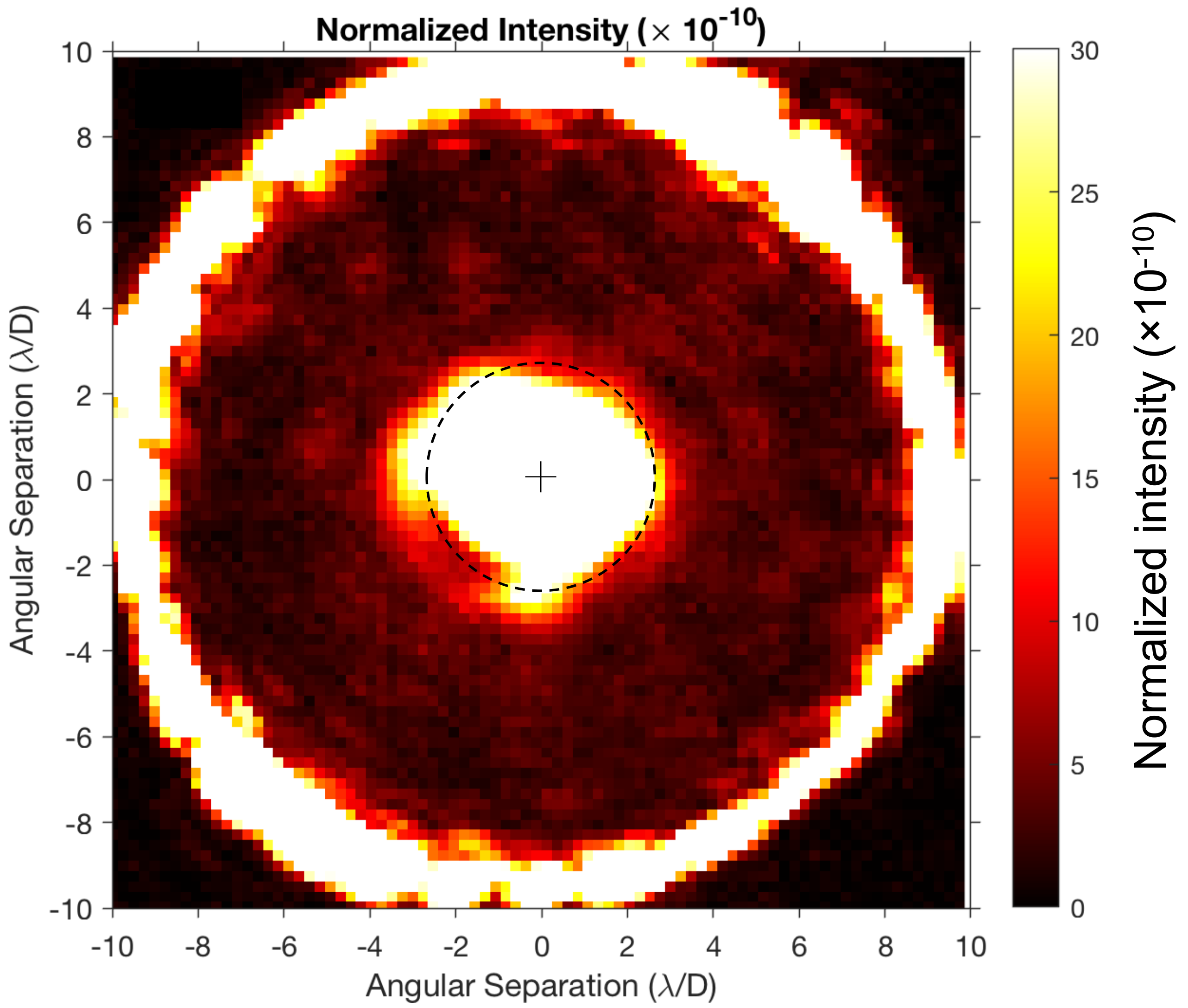
Mean contrast over **3-8 λ/D** is **2×10^{-10}** with **543 nm** HeNe laser source.



Seo et al., Proc. SPIE 111171V (2019)

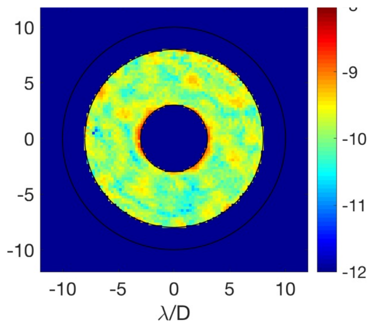
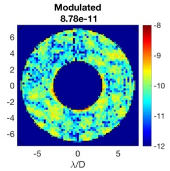
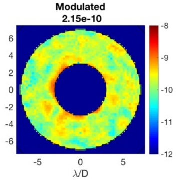
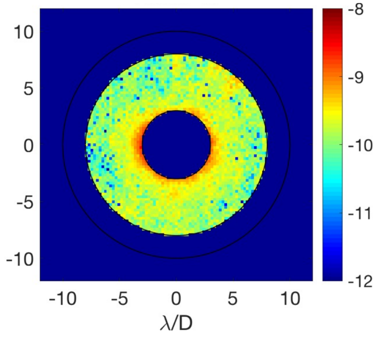
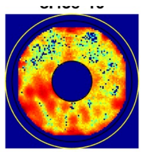
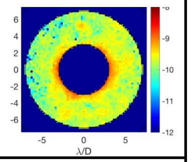
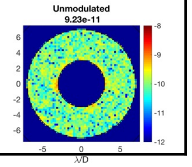
10% bandwidth dark holes reach **4×10^{-10}** mean contrast

- Spectral bandwidth = **Δλ/λ = 10%**.
- Central wavelength = **550 nm**.
- Five 2% sub-bands centered at 528, 539, 550, 561, 572 nm.
- Repeatable result.



Seo et al., Proc. SPIE 111171V (2019)

Contrast breakdown summary

Best Contrast		Measured	Morphology	
Modulated: 1.81e-10 	DM quantization error	8.78e-11	Speckle-y	
	Chromatic control Residual	9.32e-11	Speckle-y	
Unmodulated: 2.01e-10 	Occulter ghost	1.01e-10	Pattern moves with wavelength	
	Testbed Jitter	4.19e-11	Centered	
	Unknown	5.04e-11	Diffuse	

Seo et al., Proc. SPIE 111171V (2019)

Contrast breakdown summary

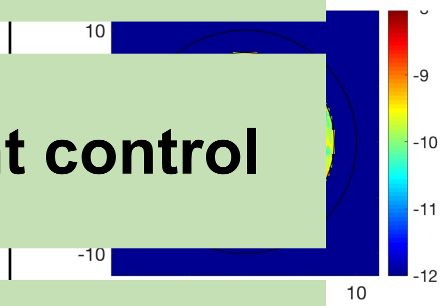
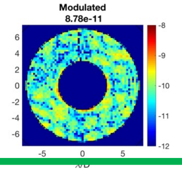
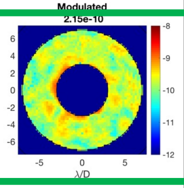
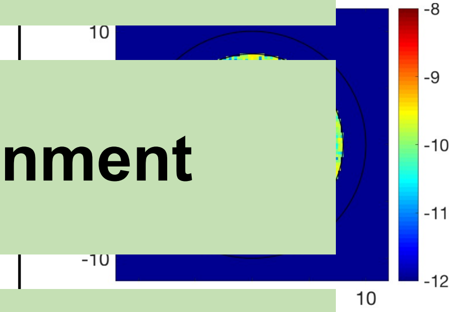
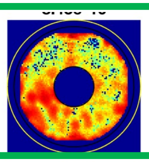
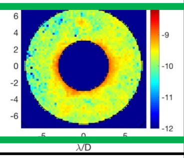
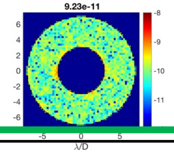
DM electronics

Wavefront control

Coronagraph mask design and fab

Environment

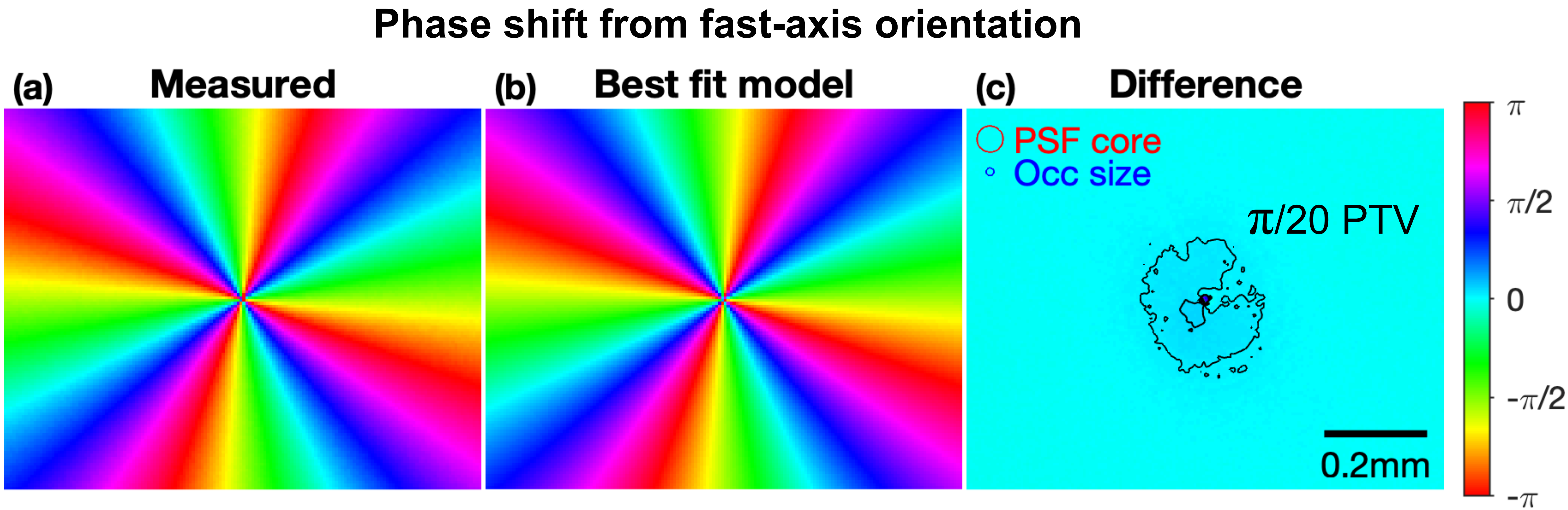
Detector calibration

Contrast		Measured	Morphology
1e-10 	DM quantization error	8.78e-11	Speckle-y 
	Chromatic control Residual	9.32e-11	Speckle-y 
2.01e-10 	Occulter ghost	1.01e-10	Pattern moves with wavelength 
	Testbed Jitter	4.19e-11	Centered 
	Unknown	5.04e-11	Diffuse 

Seo et al., Proc. SPIE 111171V (2019)

1b. Vector Vortex SAT (PI: Eugene Serabyn, JPL)

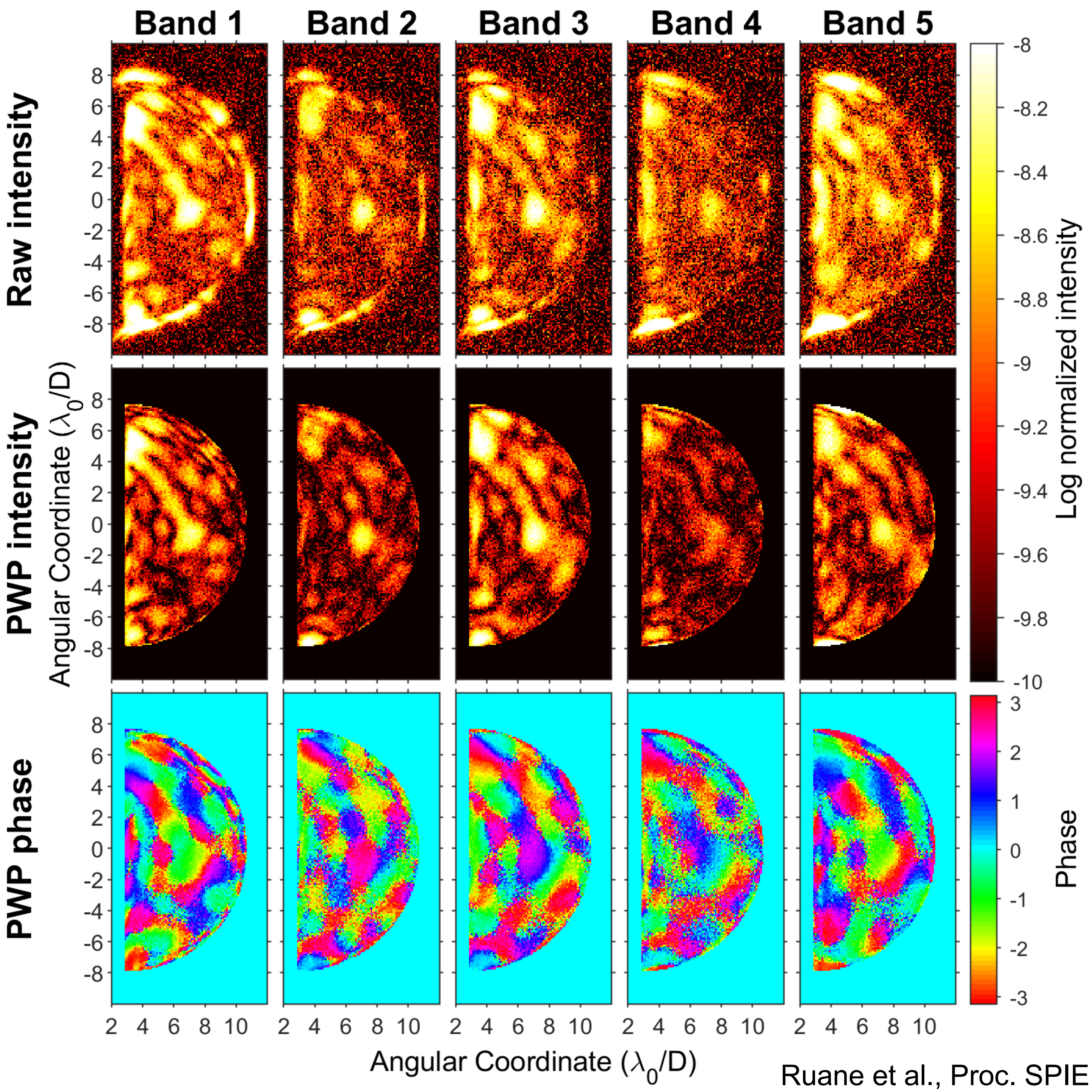
Similar set-up, but coronagraph masks



Ruane et al., Proc. SPIE 1218024 (2022)

The contrast is limited by light that modulates with the DM probes.

Mean raw NI = 1.6e-9
10% bandwidth
λ_0 = 635nm
3-10 λ_0/D dark hole



Ruane et al., Proc. SPIE 1218024 (2022)

Contrast budget can explain current floor at 10% BW

Component	**Error**	**Mitigation strategy**	**Contrast estimate**
Deformable mirror	Quantization error	Next-gen DM electronics	~1e-10 for AOX + gen5 electronics
	Drift	Temperature control	Negligible.
Testbed	Tip/tilt jitter	Vibration isolation	Negligible.
	Circular analyzer	Procure the highest possible quality QWPs and LPs	~4e-10 with polarization filtering and monochromatic laser (637nm).
Vortex mask	Bulk retardance error (ε) (a.k.a on-axis leakage)	Minimized during FPM manufacture	
	Fine scale retardance error (amp. & phase)		~2e-10 (highly chromatic)
	Fast axis orientation error (phase)		~1e-10. To be confirmed. (highly chromatic)
	Local transmission errors		~2e-10. To be confirmed. (highly chromatic)
		Total:	**~1e-9**

Ruane et al., Proc. SPIE 1218024 (2022)

Contrast budget can explain current floor at 10% BW

DM electronics

Coronagraph mask design and fab

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Testbed	Tip/tilt jitter		Negligible.
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	Local transmission errors		~2e-10. To be confirmed. (highly chromatic)
		Total:	**~1e-9**

Ruane et al., Proc. SPIE 1218024 (2022)

2. More recent successes in HCIT

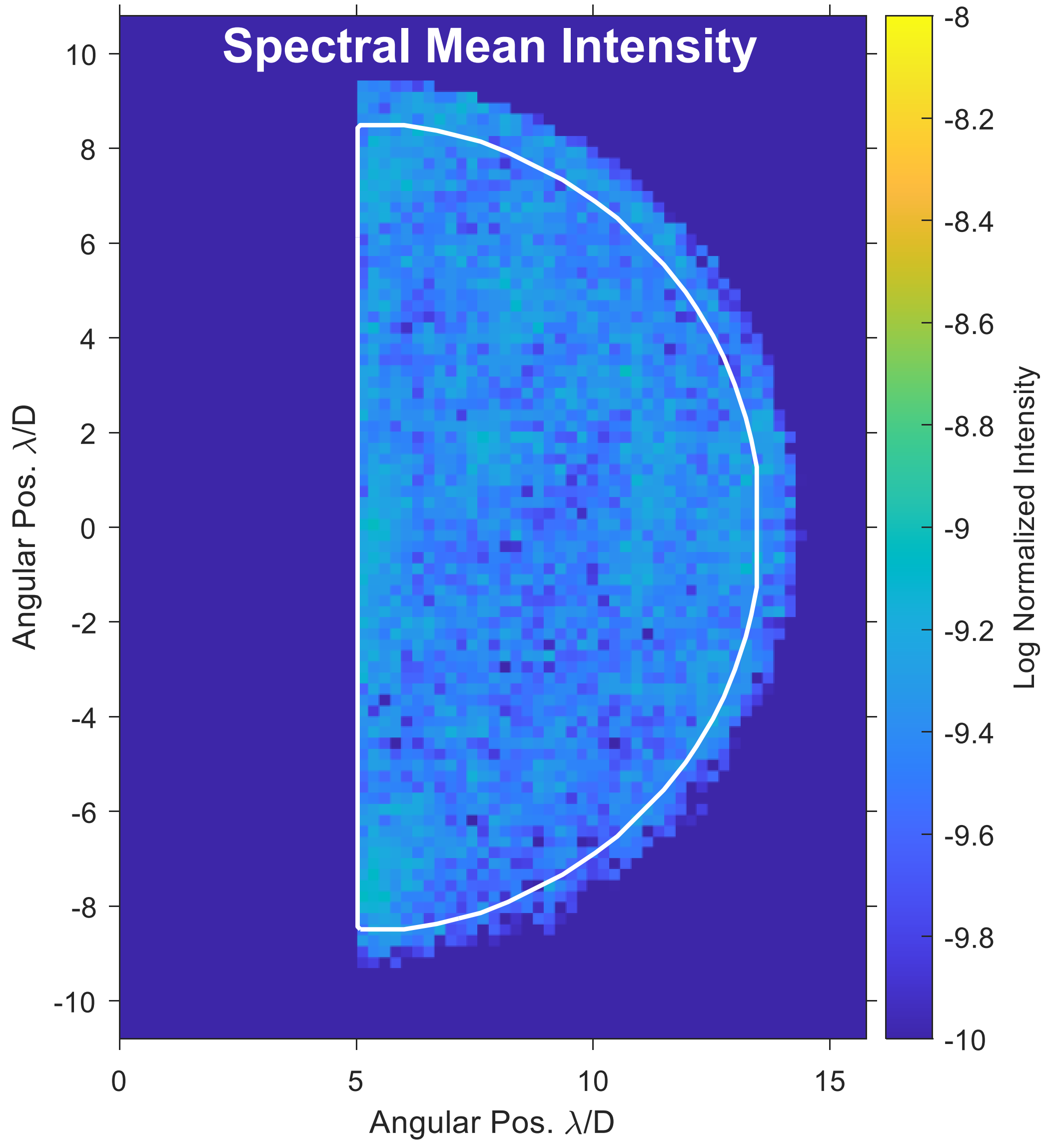
Lyot coronagraph broadband "spectroscopy" mode

(SAT PI Dimitri Mawet, Caltech)

$4{\times}10^{-10}$ Contrast in <u>20% BW</u>

Lyot Coronagraph
2 AOX DMs

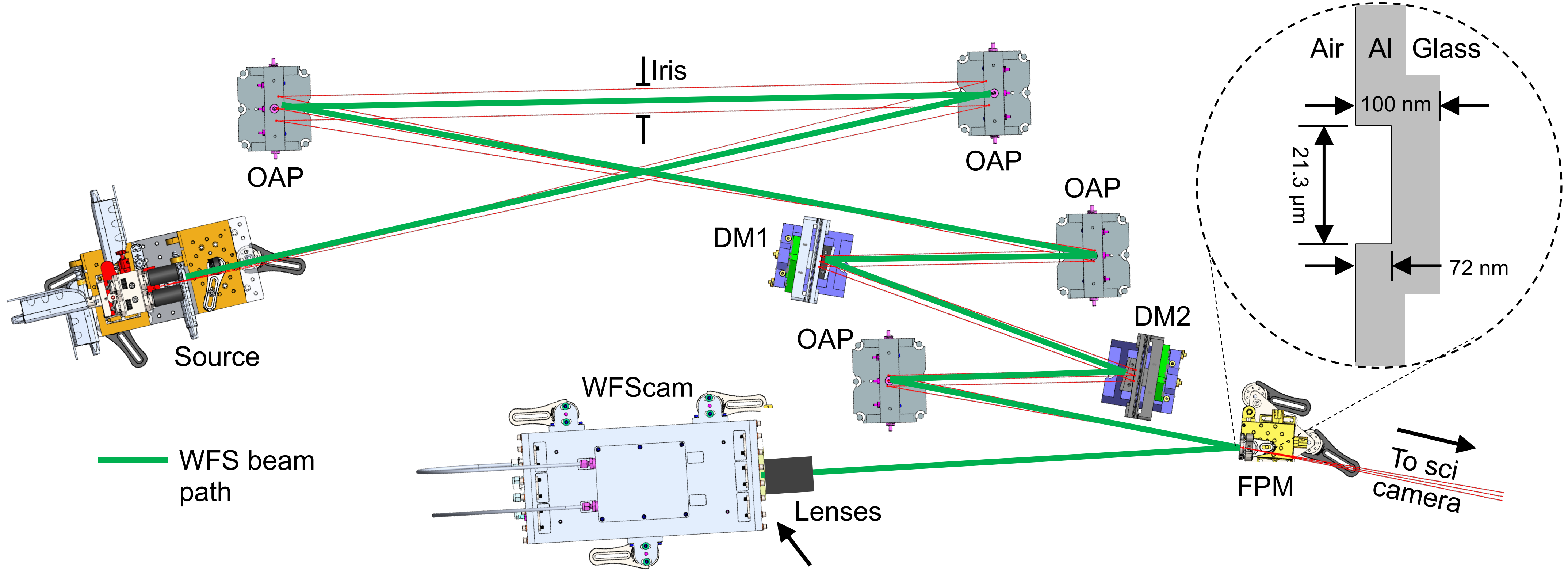
Mean Raw NI	**$4{\times}10^{-10}$**
λ_0	560 nm
Bandwidth	**20%**
Scoring Zone	5-13.5λ_0/D
DMs	2× AOX 2k
Single Polarization	

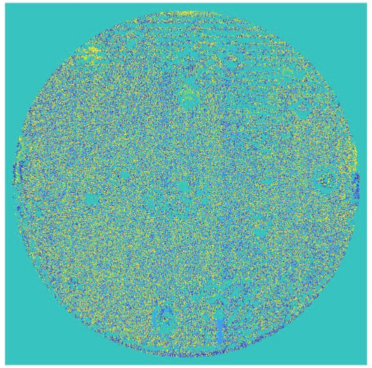


Broader bandwidth achieved through optimization of <u>wavefront control</u>

Allan et al., Proc. SPIE, in prep.

Picometer wavefront sensing and metrology





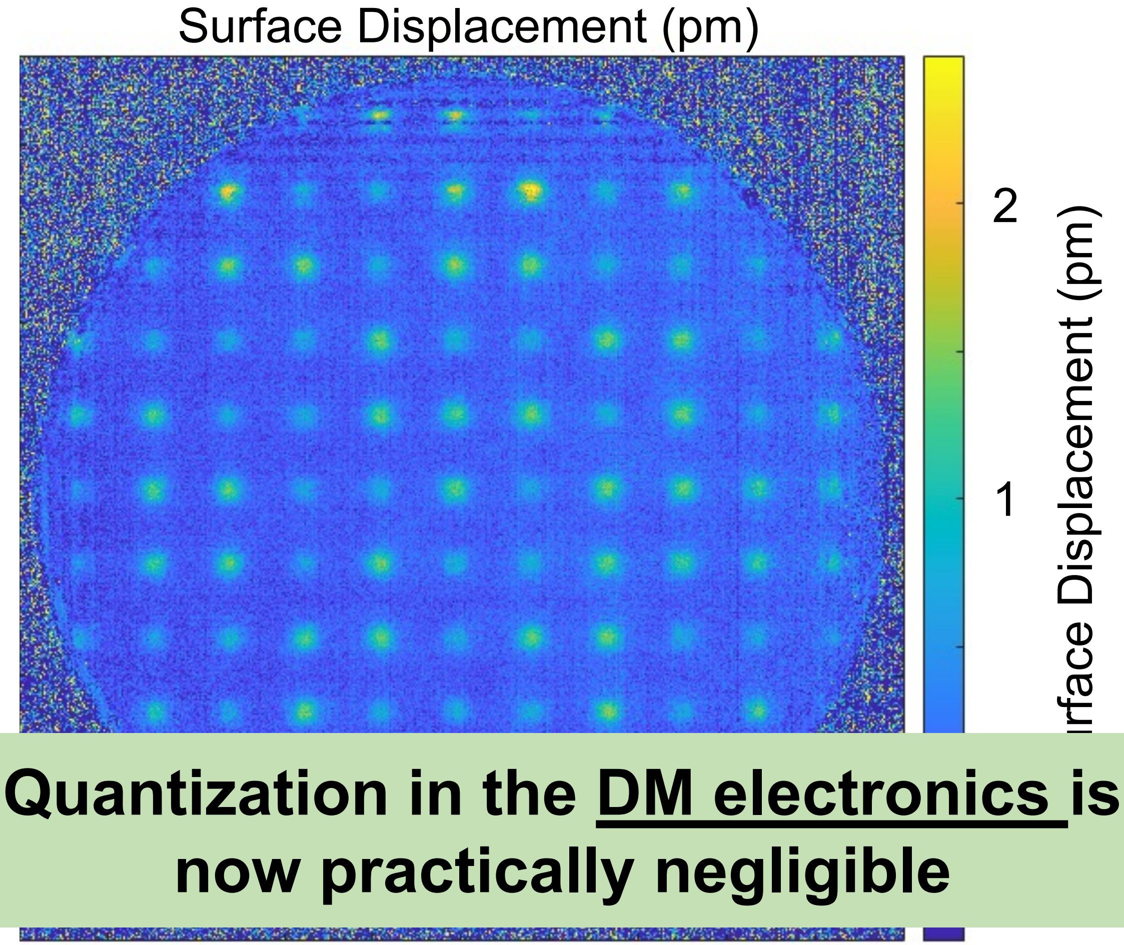
Raw ZWFS data when poking rows and columns on DM1

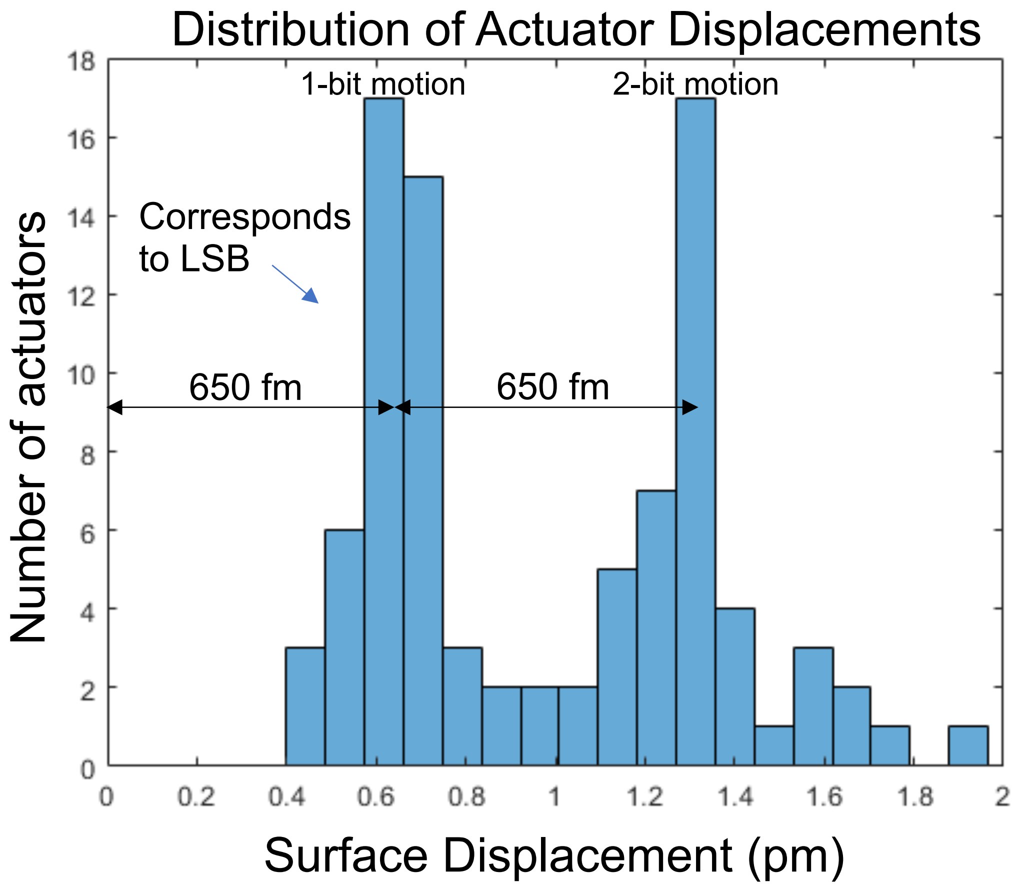
Ruane et al., JATIS 6(4), 045005 (2020)

Sub-picometer actuation demonstration on DST-2

- Measured motions of 92 actuators on BMC 2K DM
- Poke command corresponds to ~1pm
- 10,000 frames, ~14 hrs total integration time

Poke amplitude for ~1pm	190 µV
Estimated resolution	650 fm (120 µV)





Quantization in the DM electronics is now practically negligible

Bendek, Allan, Ruane, et al., in prep.

3. An incomplete list of needs moving forward

Needs: Technology investments

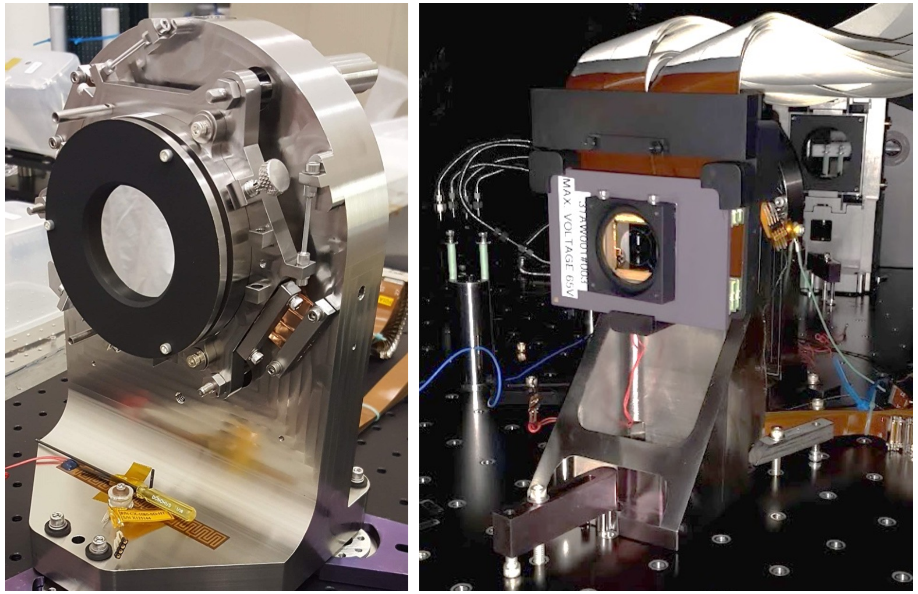
Key coronagraph components

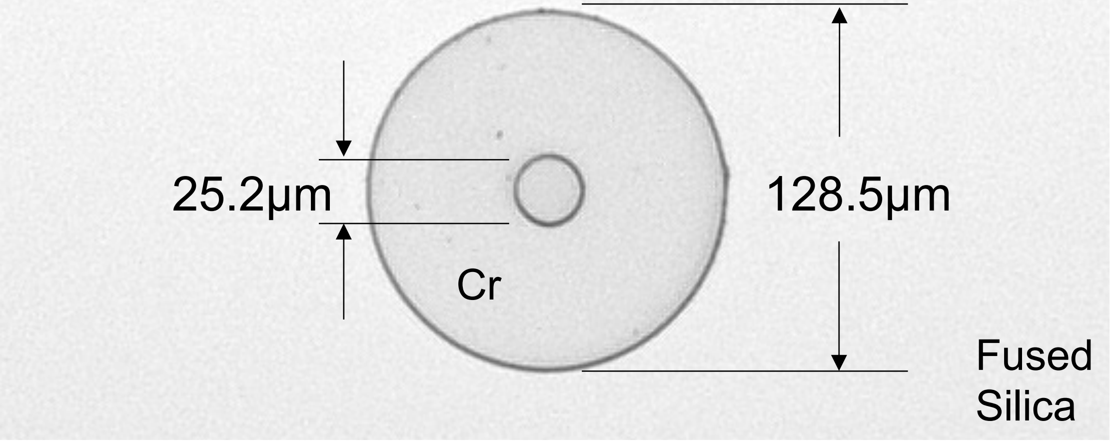
- Deformable mirrors
- Coronagraph masks
- Detectors, spectrographs, wavefront sensors, software, algorithms, flight computers, fast steering mirror, reduced surface error OAPs,

Aspects:

- Design
- Manufacturing
- Metrology and characterization
- Processing and handling
- Interfaces

The DST DMs



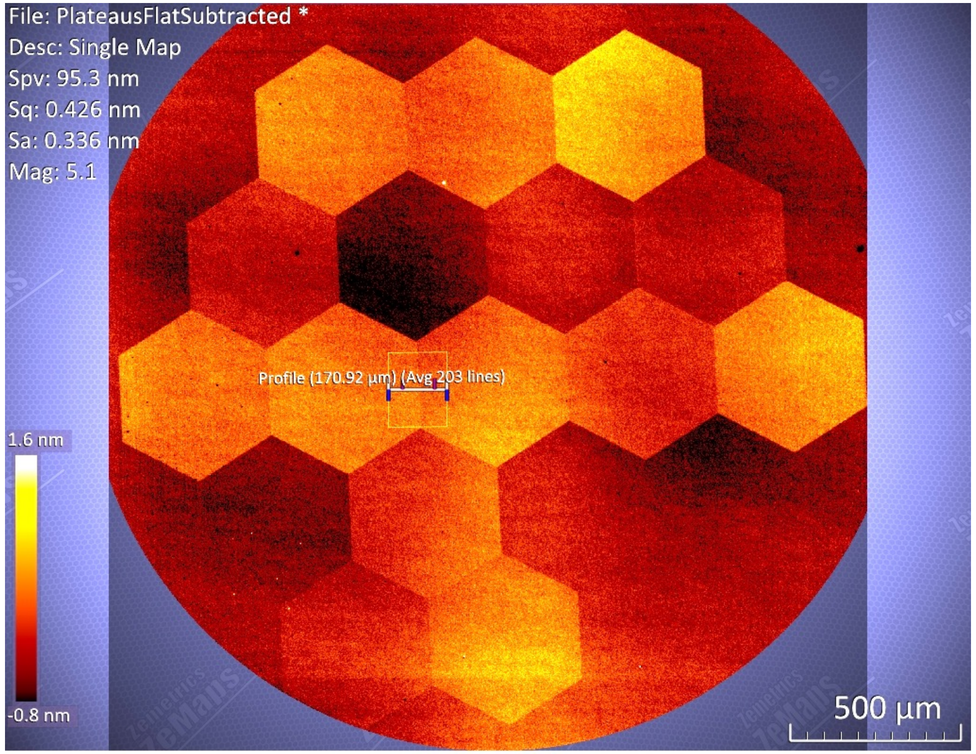


Lyot occulter

Needs: Testbed demonstration programs

- Testbed demonstration milestones that meet TRL 5 and 6 requirements
- Coordinate testbed activities across institutions.
- Dedicated testbed efforts for model validation and uncertainty quantification
- Realistic wavefronts (aberrations, segments, jitter, shearing, etc)
- Sensitivity measurements

Example static segmented wavefront mirror



Courtesy of Dan Shanks (JPL Microdevices Lab)

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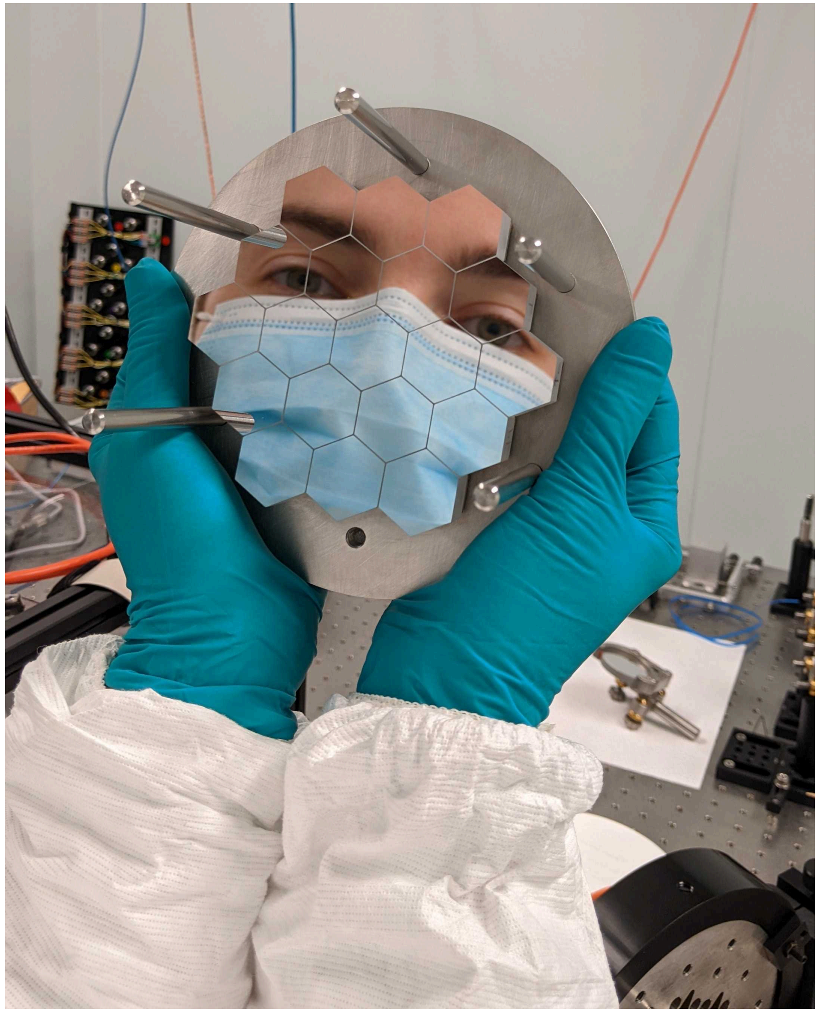
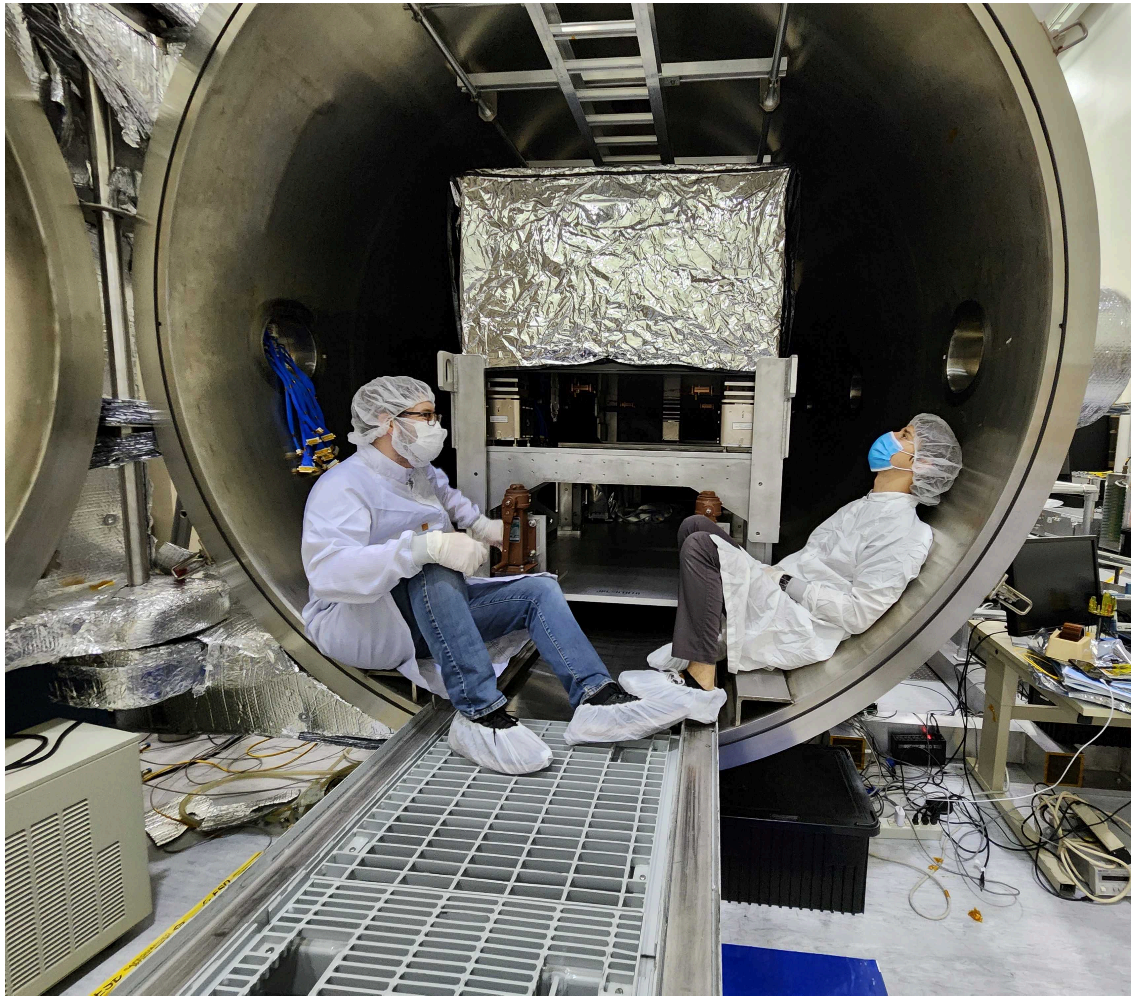


courtesy of Emiel Por

Needs: Programmatic

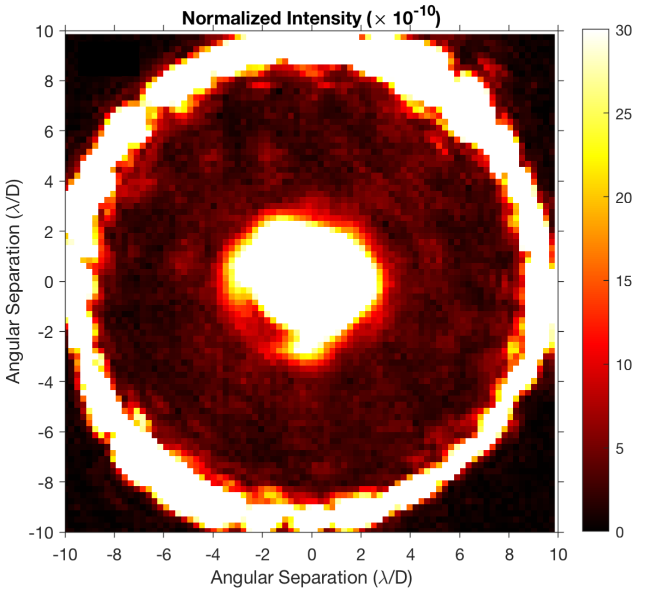
Directed funding to support:

- Modeling and error/contrast budgets
- Stable, experienced testbed operator workforce
- Process control
- Detailed mask characterization
- Testbed-result-driven coronagraph design and modeling

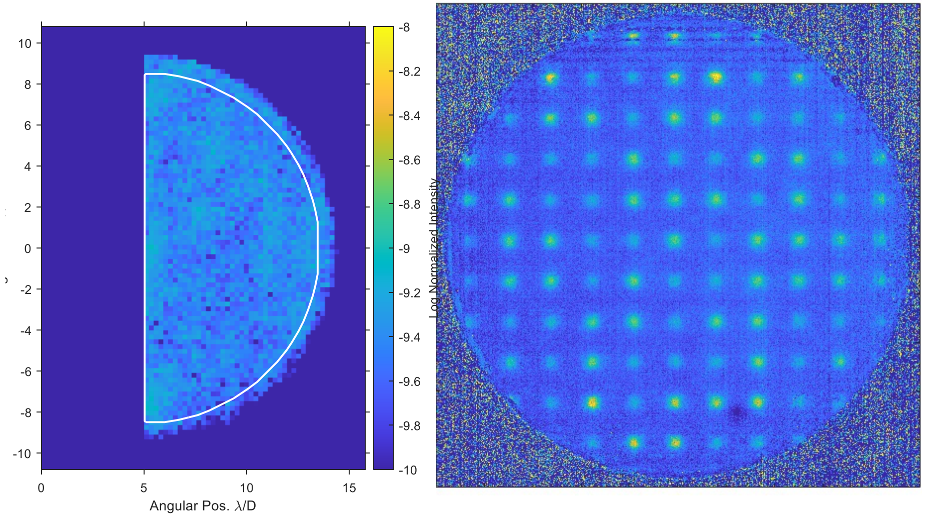


Summary

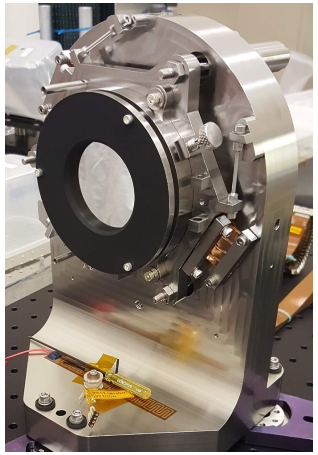
Record is 4×10^{-10} in 10% BW

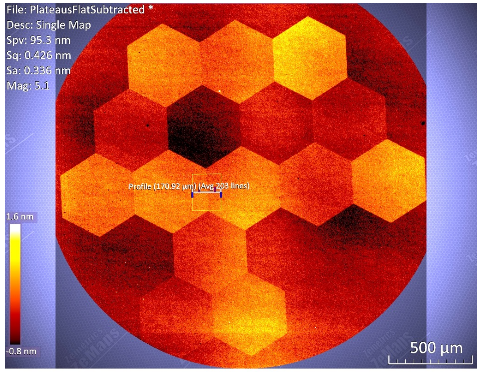


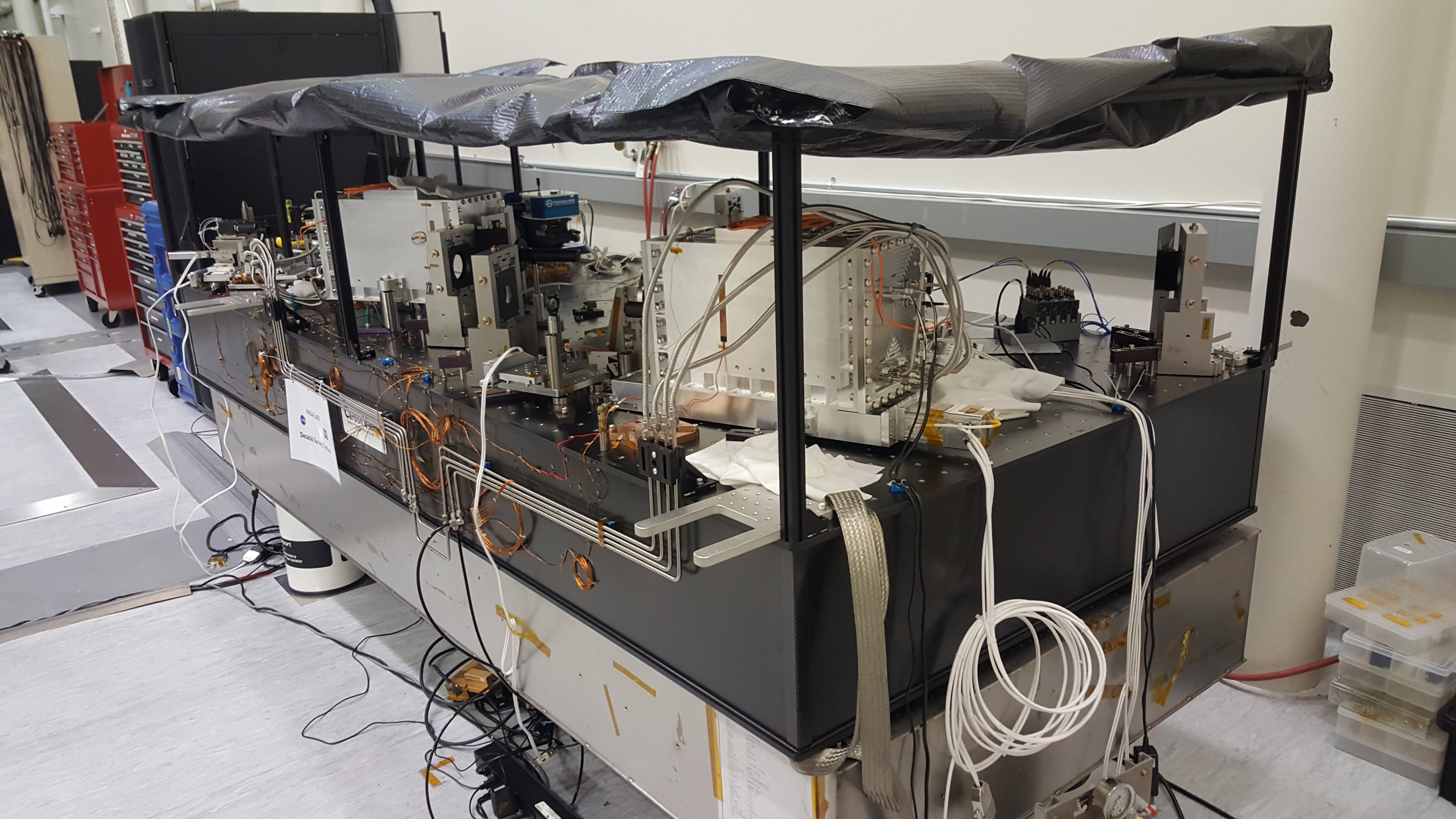
New data shows 4×10^{-10} in 20% BW and sub-picometer DM actuation



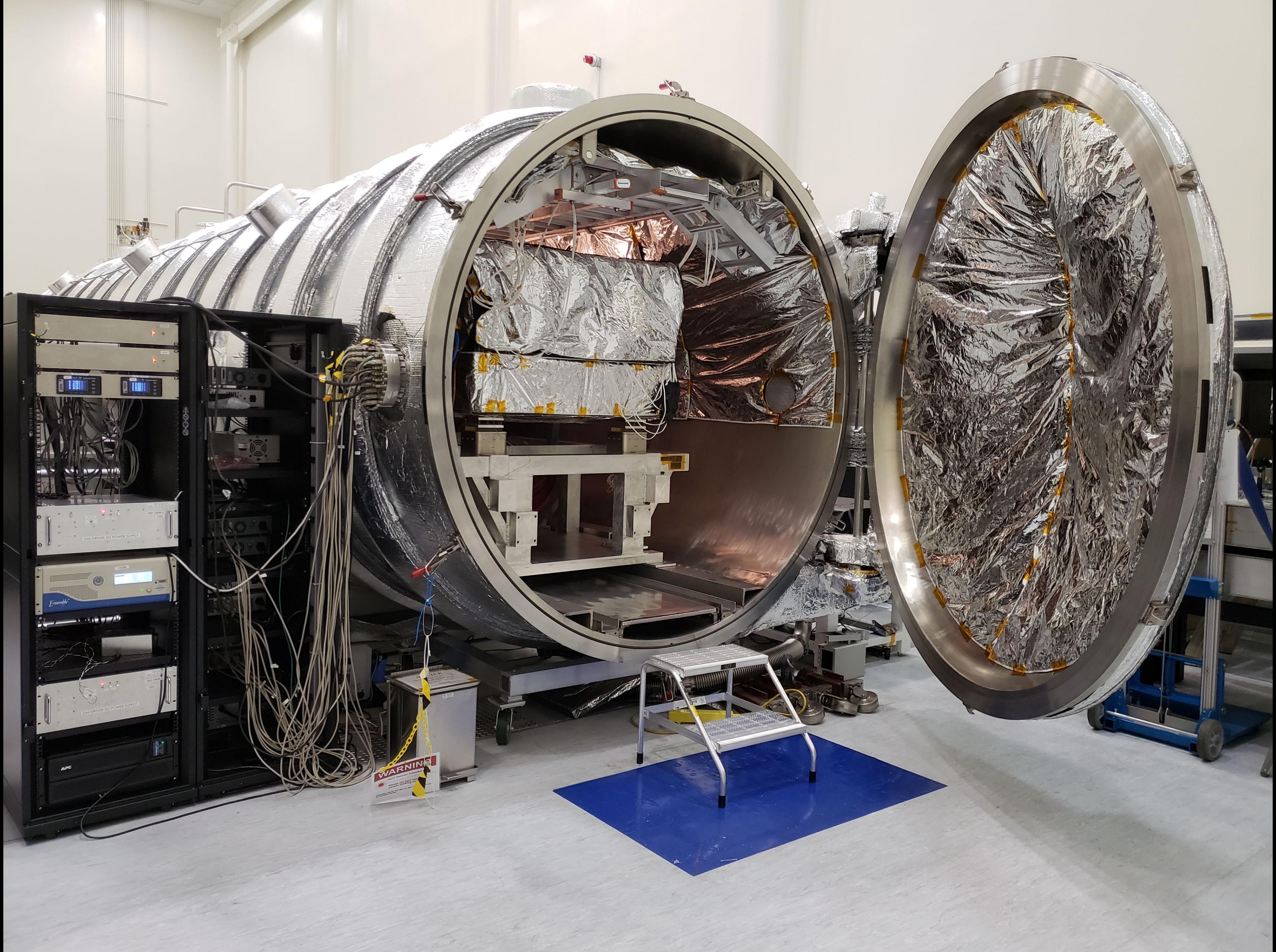
But we have work to do!






NASA ExEP
Decadal Survey Testbed

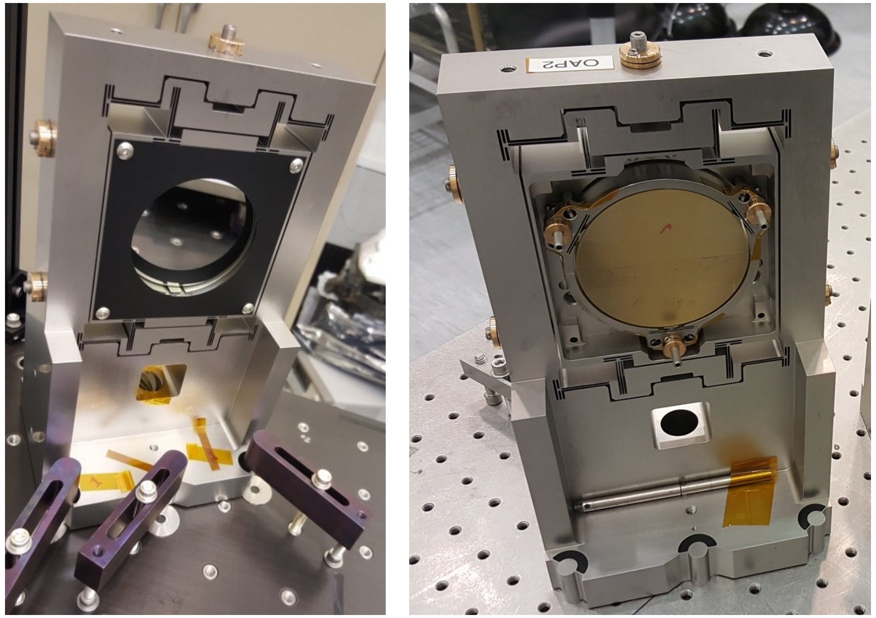

CarbonVision
EXIT


DM1 DM48.4
100V
DM DRIVER 5G POWER SUPPLY
Ensemble
DM2 DM48.5
100V
DM DRIVER 5G POWER SUPPLY
APC
WARNING

For very high contrast, stability is paramount!

- Tight stability requirements
- Minimal vibration
- <1 mK temperature control
- <1 mTorr vacuum

Custom titanium OAP mounts



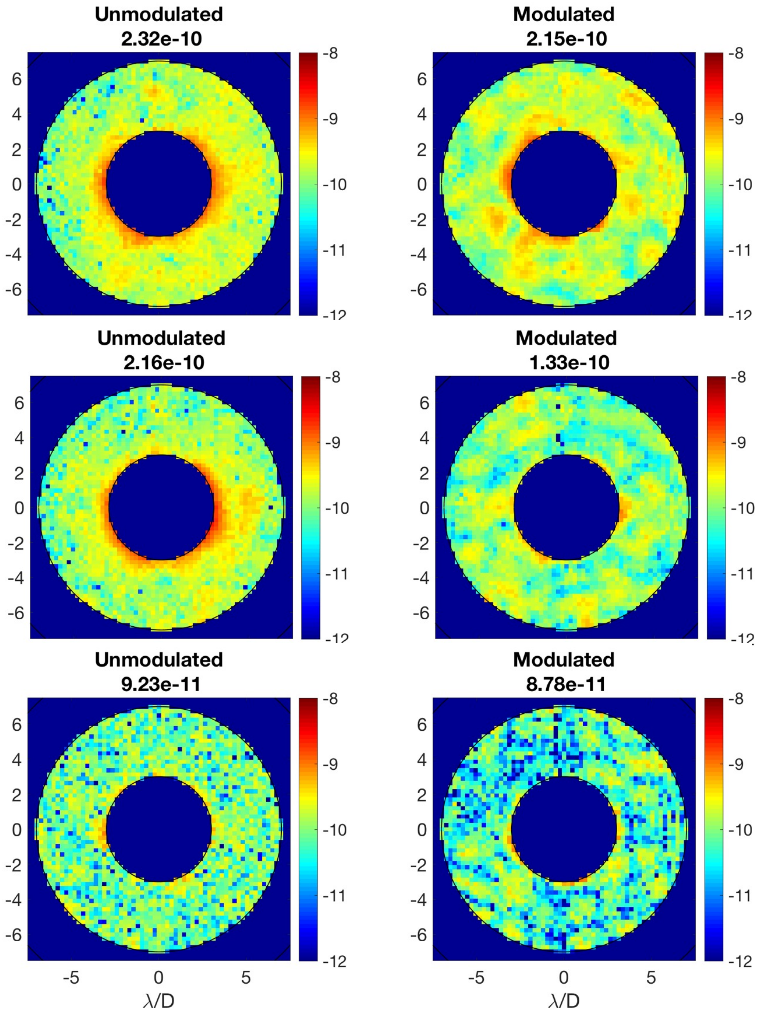
Carbon composite table

Contrast breakdown

(a) 10 %
Full DH

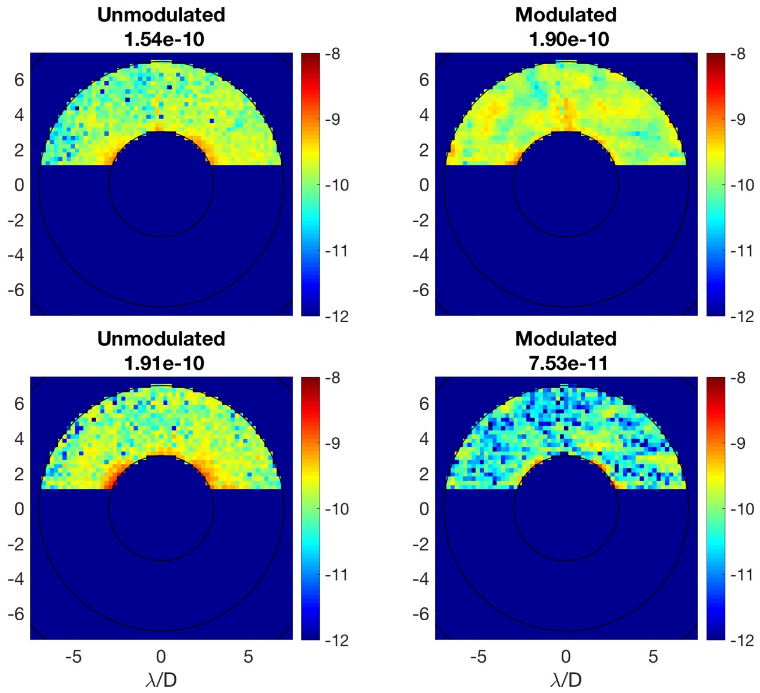
(b) 6 %
Full DH

(c)
Monochromatic
Full DH
(HeNe 543 nm, coherent
length > 0.5 m)



(d) 10 %
Half DH

(e) 2 %
Half DH



- **Smallest modulated light at full DH is 8.78e-11, shown in (c). Consistent with DM LSB effect of 1e-10.**
- **The 10% chromatic control residual is 9.32e-11, which is 1.81e-10 (best modulated) – 8.78e-11 (LSB effect)**
- **Smallest unmodulated with full DH is 9.23e-11, shown in (c). Excluding the testbed jitter impact (4.19e-11), unknown unmodulated light is 5.05e-11.**
- **Increase of umodulated light from HeNe to Broadband laser is 1.09e10, which is 2.01e-10 (best unmodulated page 5) – 9.23e-11 (HeNe). Consistent with occulter ghost.**

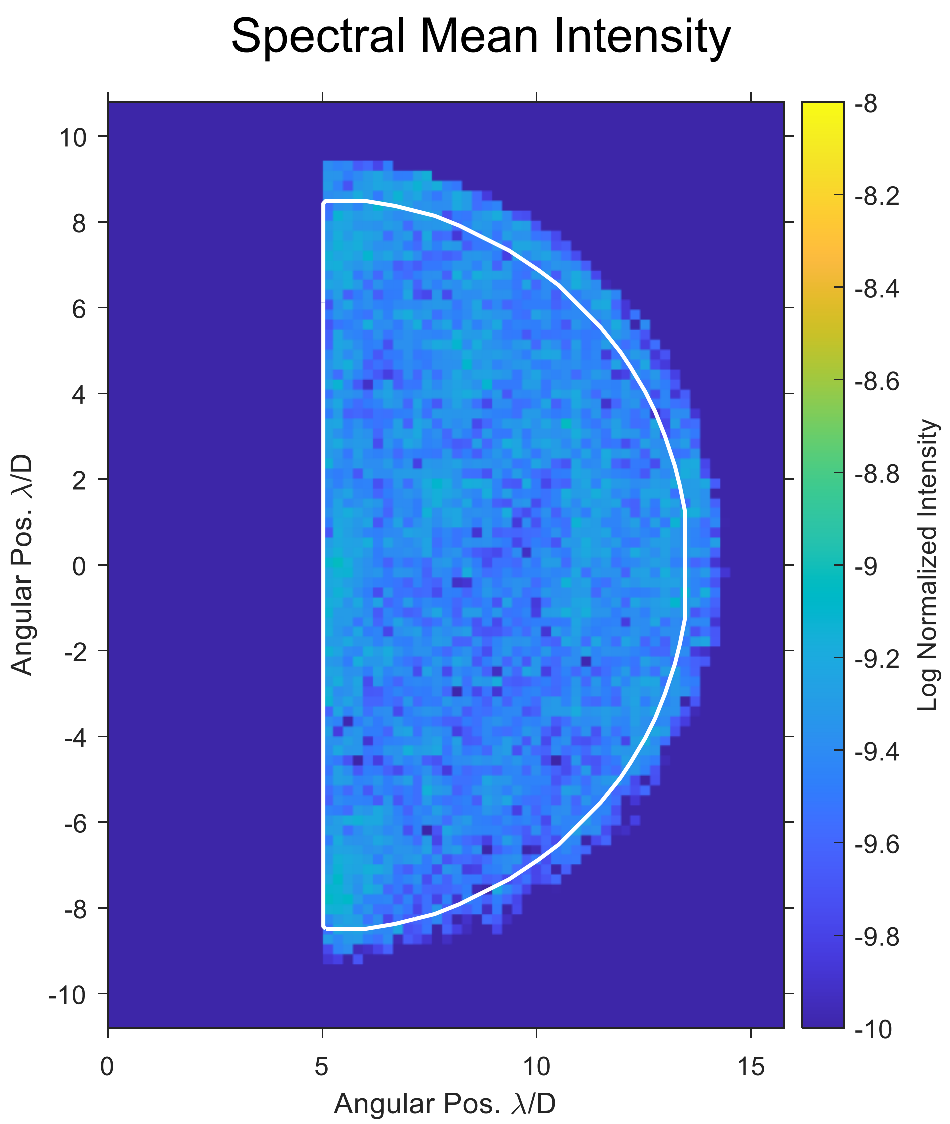
Courtesy of Joon Seo (JPL)

Wide-band contrast on the Decadal Survey Testbed

4×10^{-10} Contrast in 20% BW

Lyot Coronagraph
2 AOX DMs

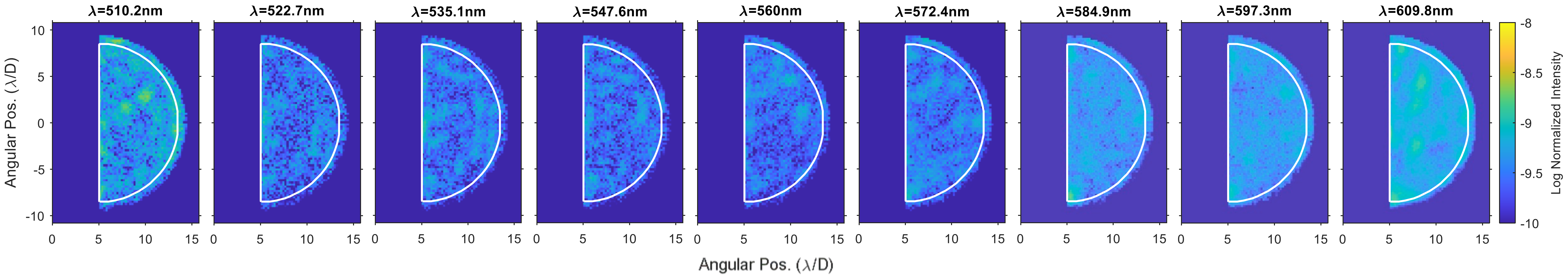
Mean Raw NI	**3.97E-10** +/- 4E-12
λ_0	560 nm
Bandwidth	20%
Scoring Zone	5-13.5λ_0/D
DMs	2x AOX 2k
Single Polarization	



Wide-band contrast on the Decadal Survey Testbed

4×10^{-10} Contrast in 20% BW

Lyot Coronagraph, 2 DMs



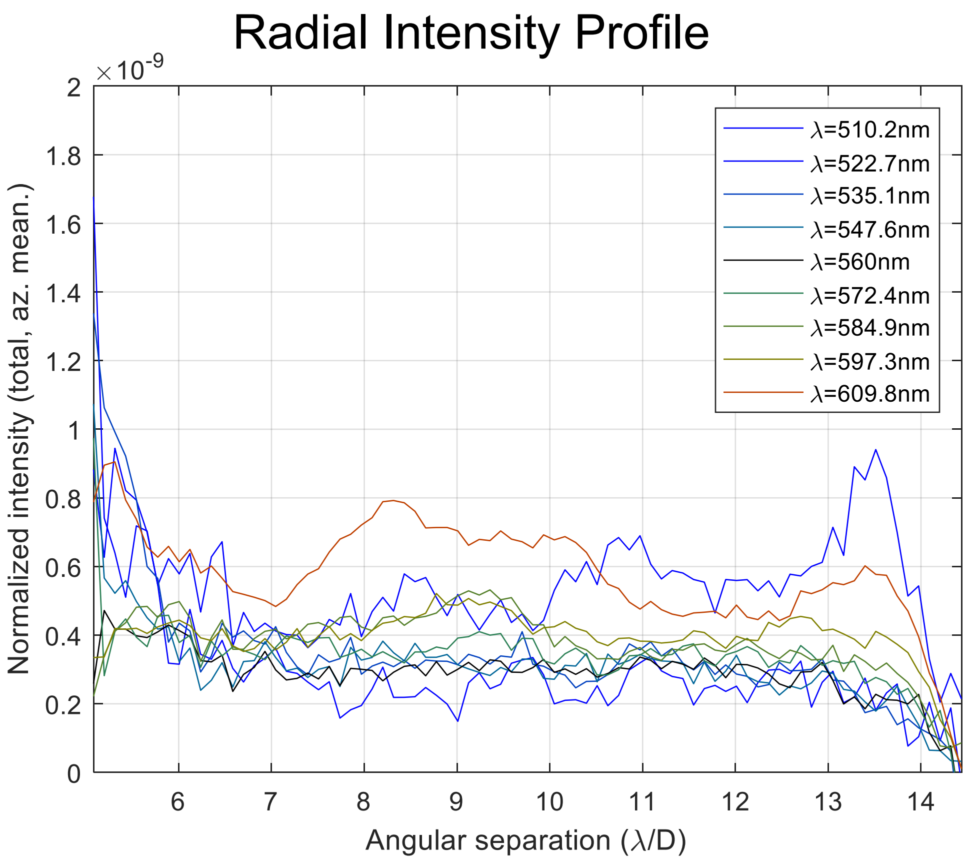
Experiment Parameters	
λ_0	560 nm
Bandwidth	20%
Scoring Zone	5-13.5λ_0/D
DMs	2x AOX 2k
Single Polarization	

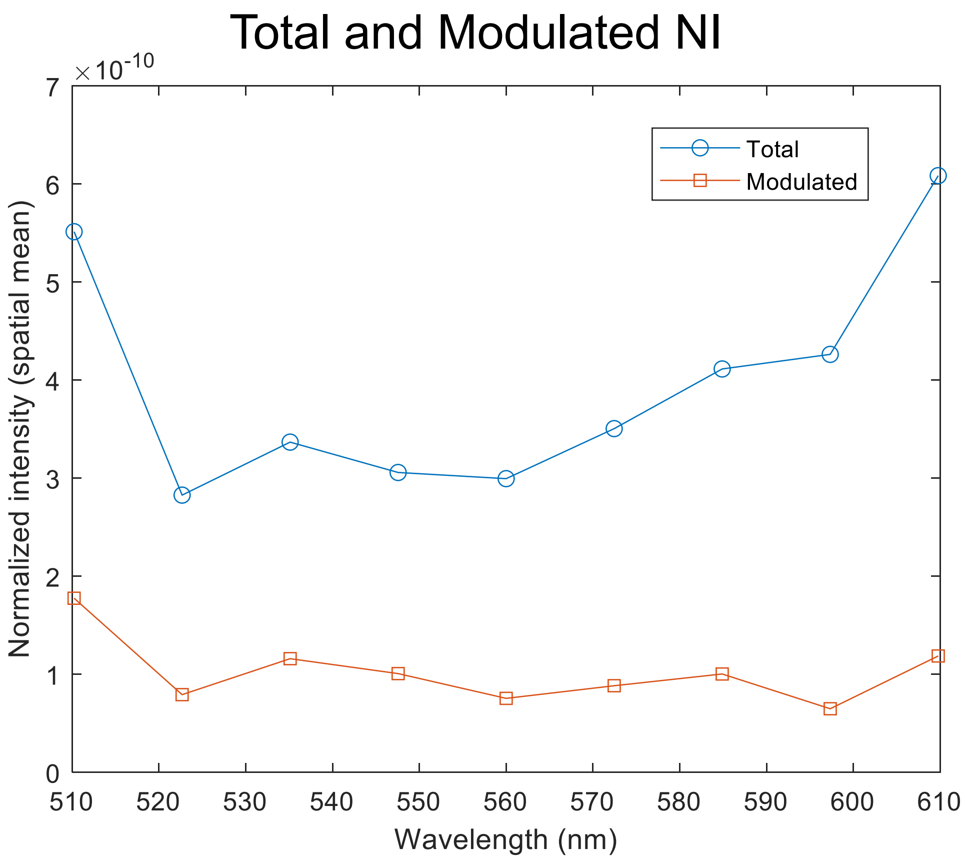
Trial	Spectral Mean NI	Uncertainty*
A	3.03E-10	+/- 9E-12
B	**3.97E-10**	**+/- 4E-12**
C	5.10E-10	+/- 6E-12

*Std. Dev. across 8 measurements (ignoring detector persistence)

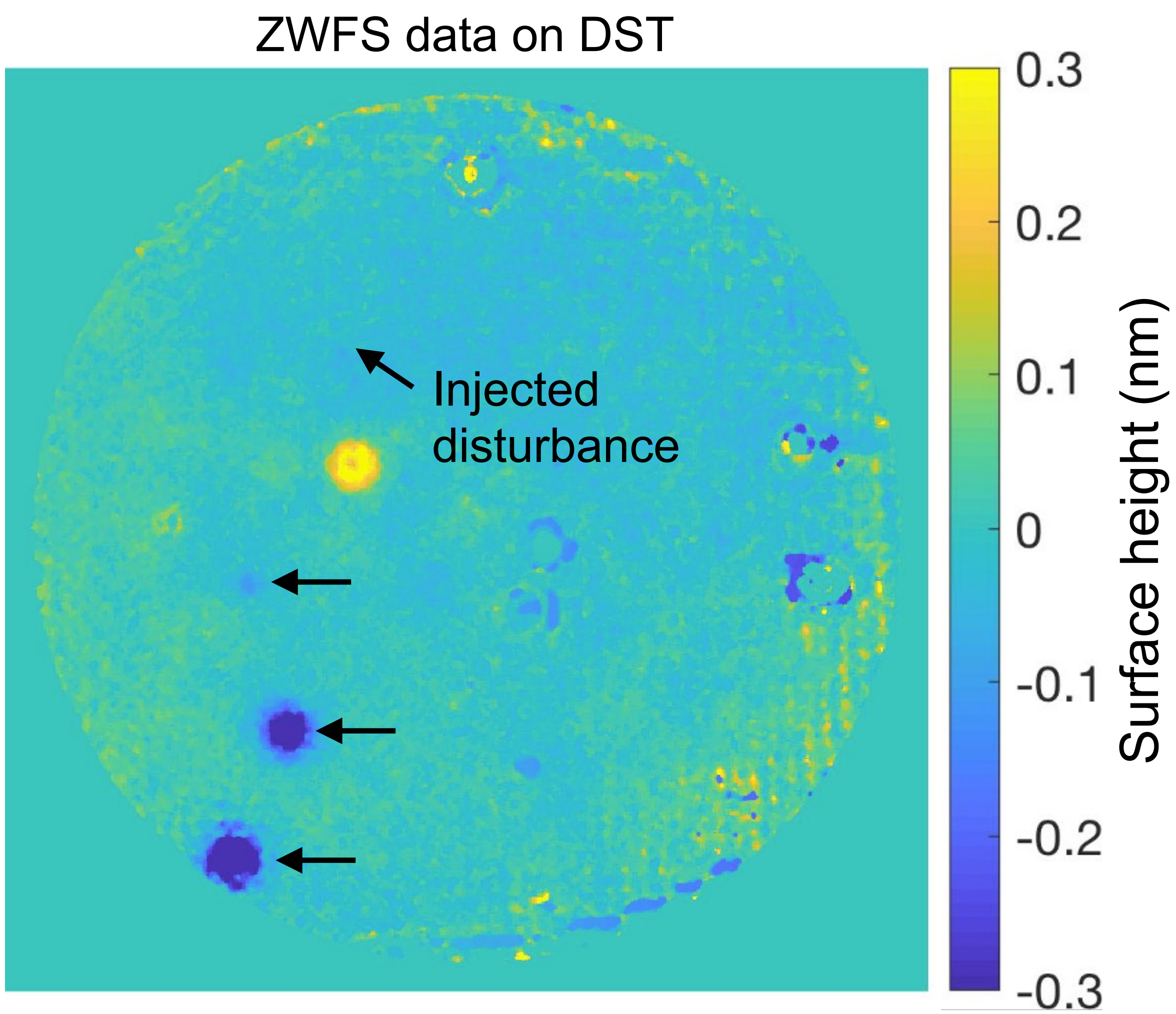
Prev. Record: 4×10^{-10} Contrast in 10% BW

Wide-band contrast on the Decadal Survey Testbed (cont.)





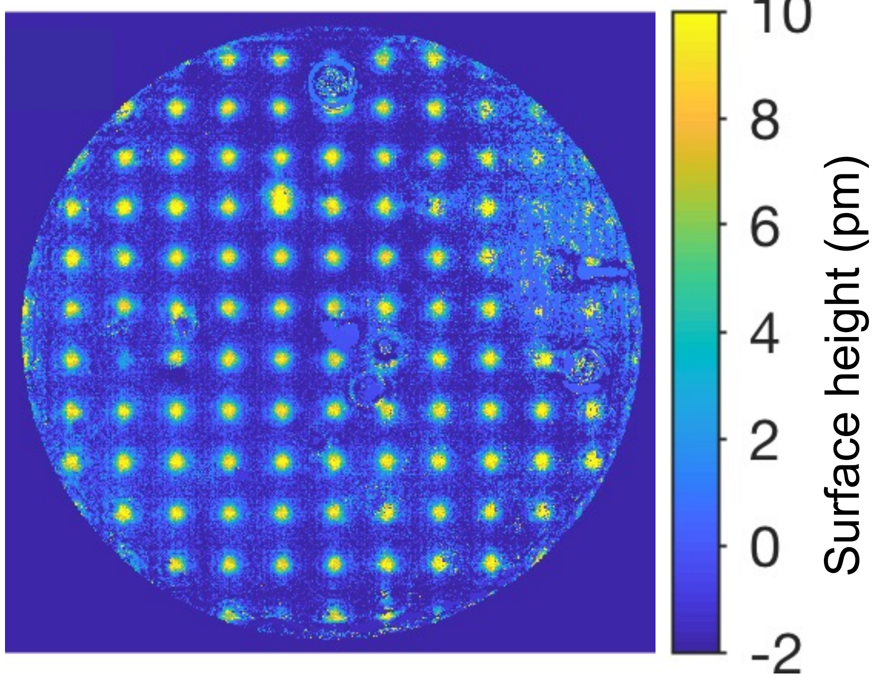
DST's WFS has proven to be a crucial diagnostic tool…



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

DM surface height resolution measurement

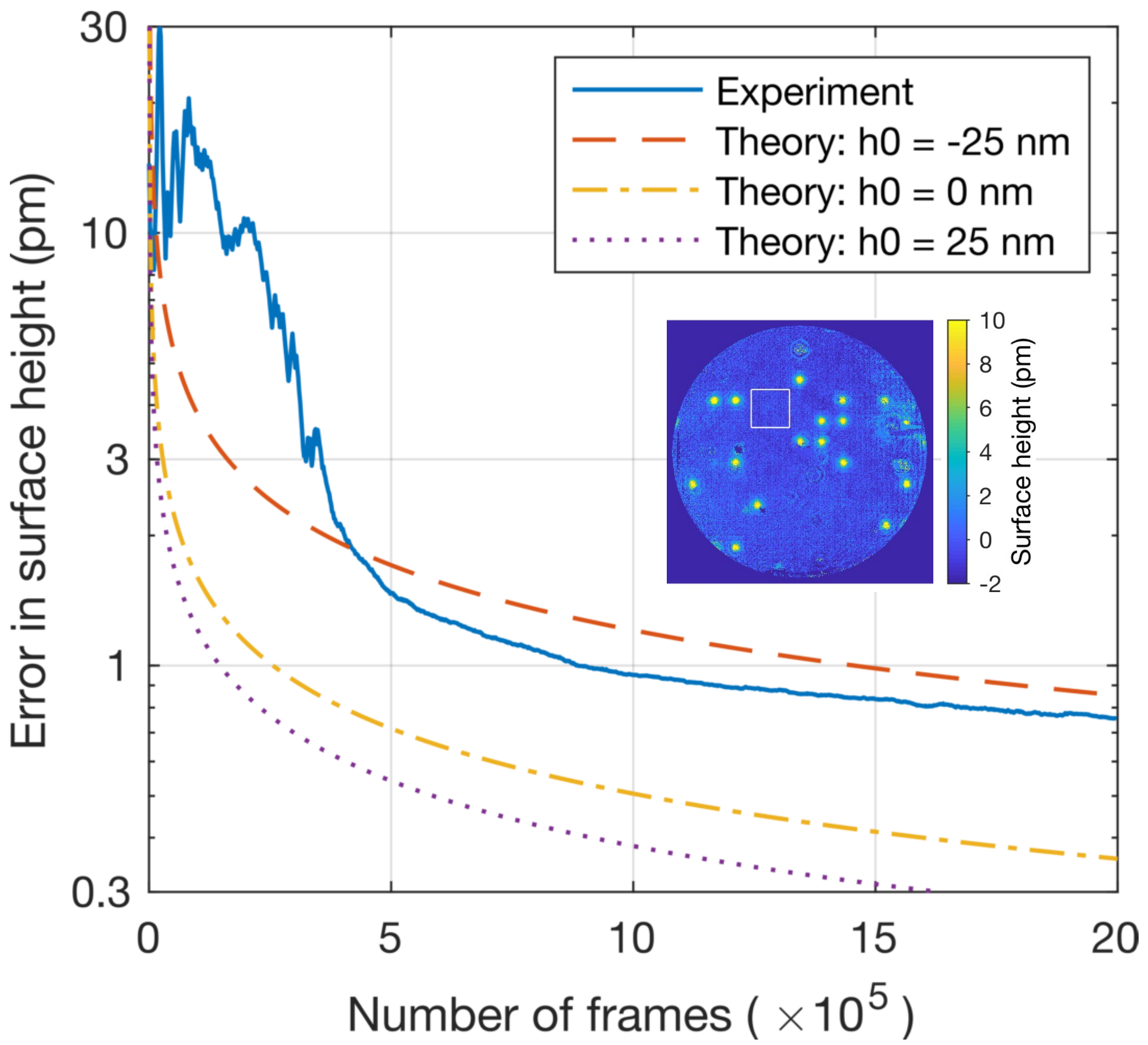
Single-bit actuator pokes



- 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.

Ruane et al., JATIS 6(4), 045002 (2020)
Ruane et al., JATIS 6(4), 045005 (2020)

Measurement agrees with theory within uncertainties

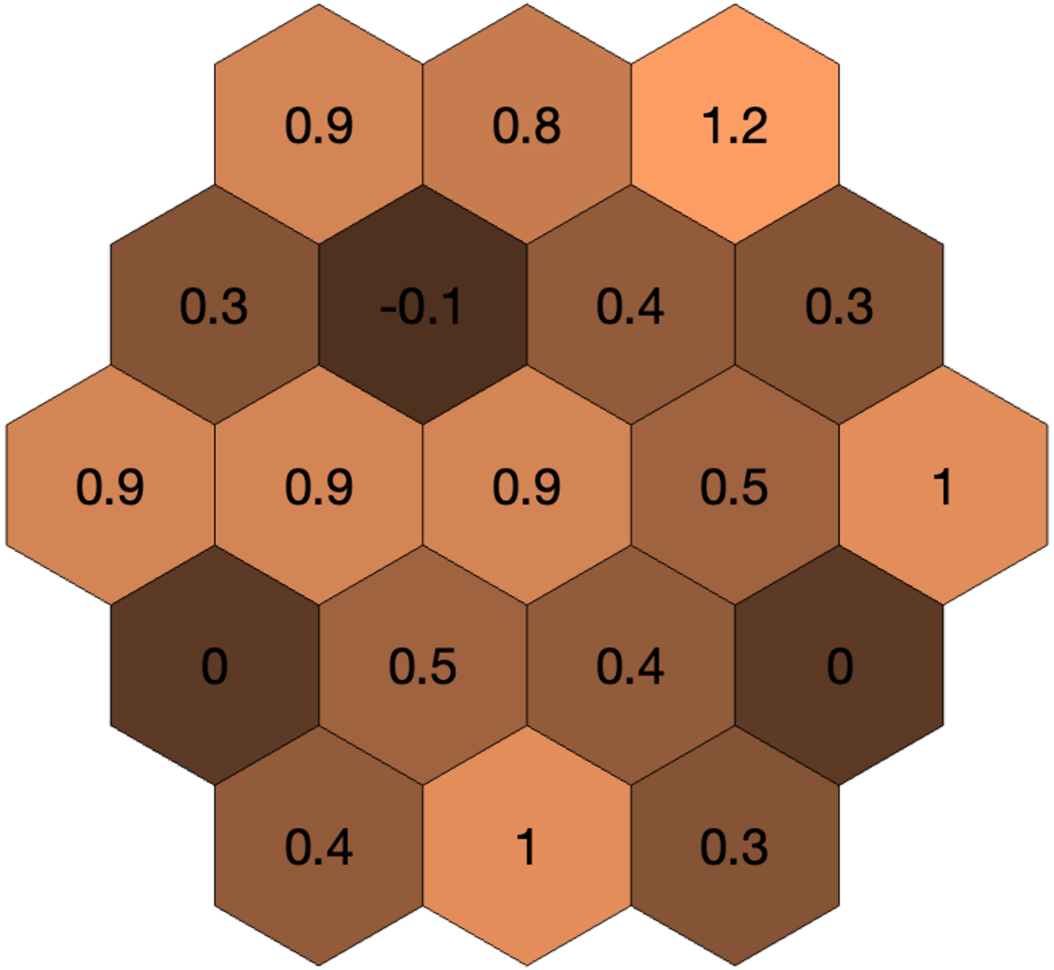


- Experimental noise measurement is within a factor of a few of ideal performance.
- Nominal WFE can account for difference in sensitivity.
- Uncertainty in WFE at the Zernike WFS mask is likely >50 nm.
- Demonstrates the possibility to measure picometer motions

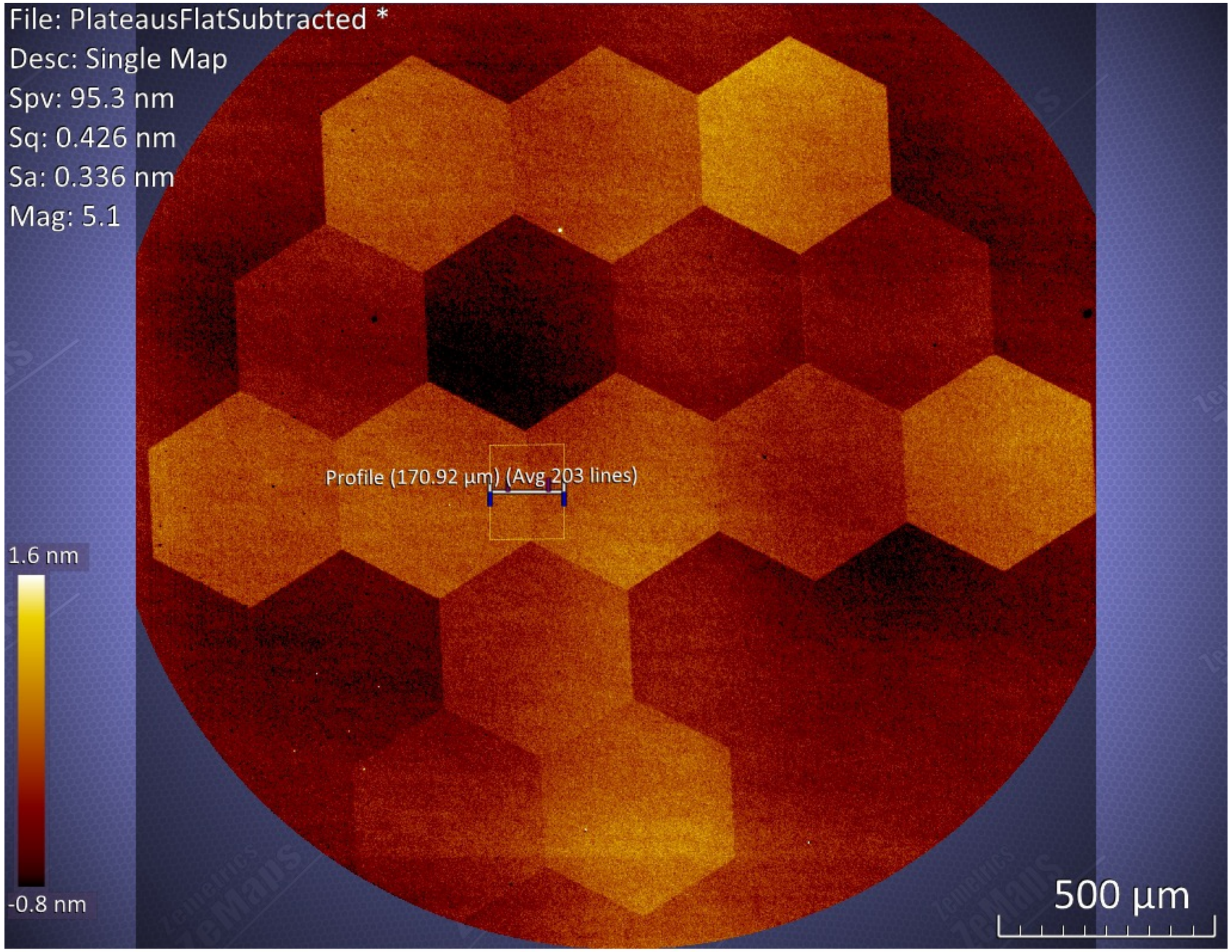
Ruane et al., JATIS 6(4), 045005 (2020)

Static segmented wavefront mirror

Surface map (nm)



Surface map via white-light interferometry



Hex width = 0.436mm
Manufactured by Dan Shanks (JPL Microdevices Lab)