Jet Propulsion Laboratory
California Institute of Technology

WFIRST CGI Milestone 9 Dynamic Contrast Demonstration Status Update

January 27, 2017

WFIRST Coronagraph Testbed and Modeling Teams

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Outline

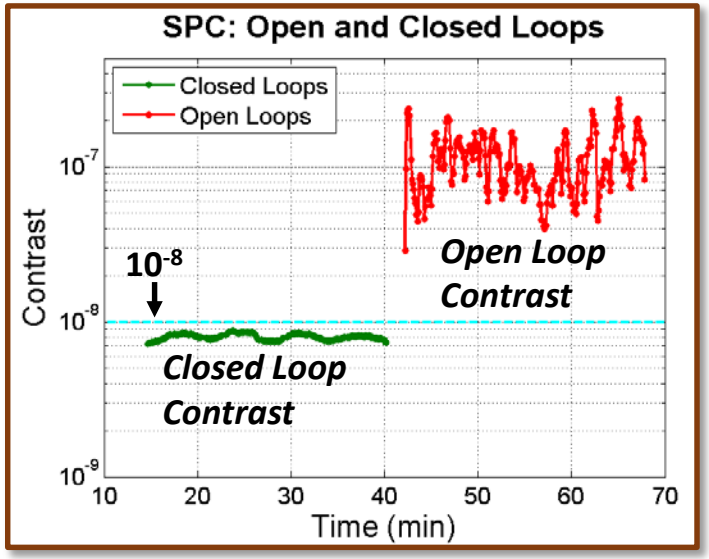
- Summary of the last Milestone 9 review
- Summary of progress since the last MS9 review
- Dynamic test results: HLC and SPC modes
- Static contrast improvements: HLC and SPC modes
- Dynamic results discussion
- Conclusion and future work
- Backup slides

MS9 Review and TAC Comments

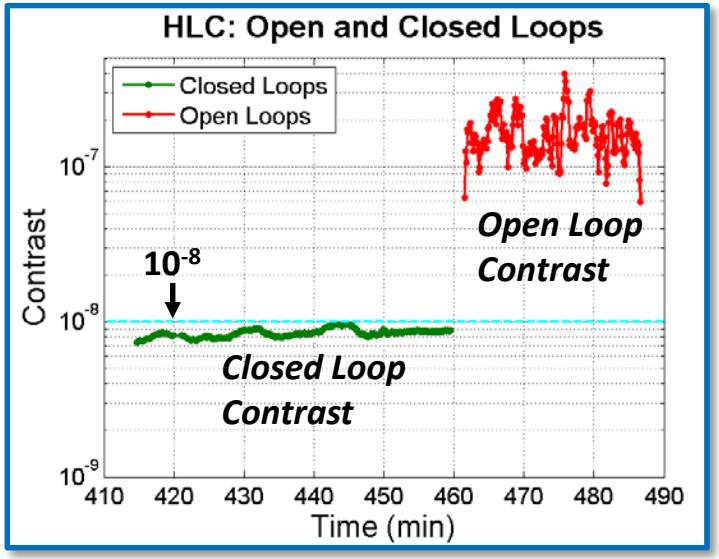
- **At the Milestone 9 review on 11/8/2016, the following results were presented:**
  - Static OMC contrast reaching 9×10^{-9} with a recently reconfigured testbed pseudo-star and OTA front end, that reduced unmodulated light
  - Dynamic test results showing LOWFS/C performance in controlling pointing and focus errors (HLC) during testing done with the earlier front end, at a worse static contrast level
  - These tests were done separately; dynamic testing with LOWFS/C had not been carried out yet with raw contrast better than 10^{-8}
- **TAC MS9 report comments:**
  - "it must be noted these quoted contrasts for Milestone #9 were obtained through static testing in the HCIT. Modeling of the expected degradation in a dynamic environment was also performed, but the contrast measurements were not performed simultaneously with the dynamic jitter."
  - "The TAC encourages the team to continue their efforts with both the SPC and the HLC in the dynamic testing environment to enable Milestone #9 to be truly achieved for either, or both, methods."
- **Scope of this review:**
  - New results showing "both the SPC and the HLC [performance] in a dynamic testing environment"
  - New results showing improved static SPC and HLC contrast performance

Summary of Testbed Results

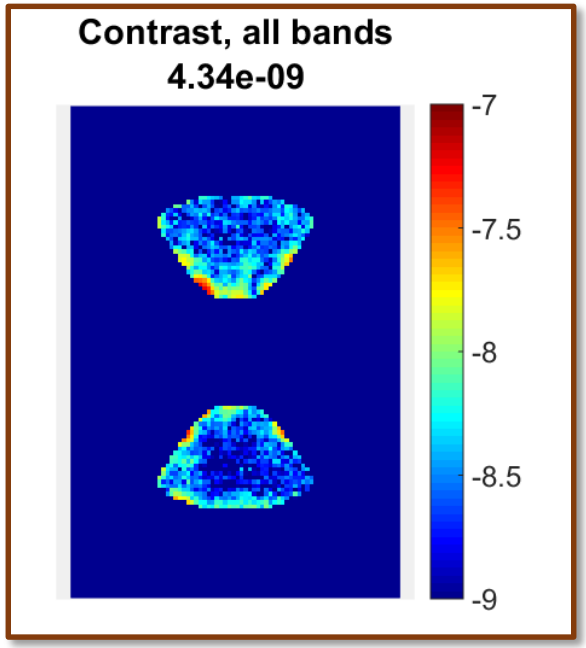
SPC Dynamic Test (10% at 550nm)



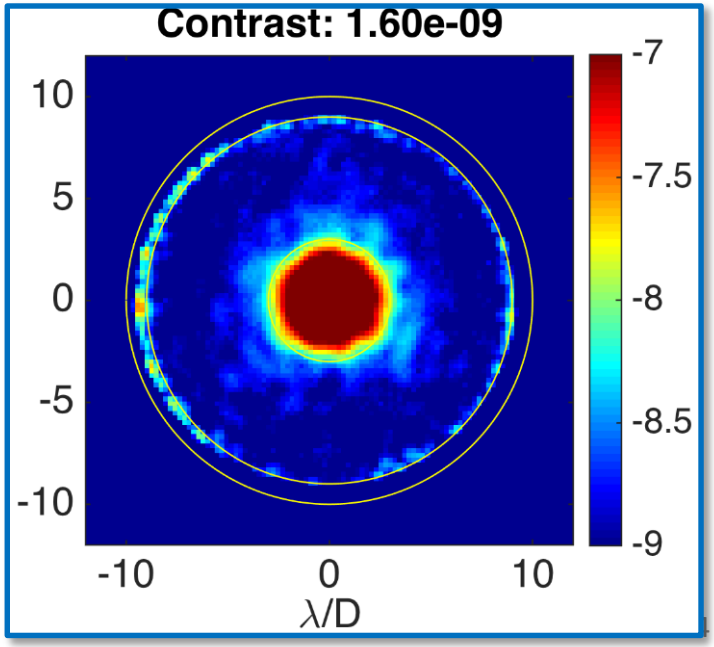
HLC Dynamic Test (10% at 550nm)



Best SPC Static Contrast (10% at 550nm)



Best HLC Static Contrast (10% at 550nm)

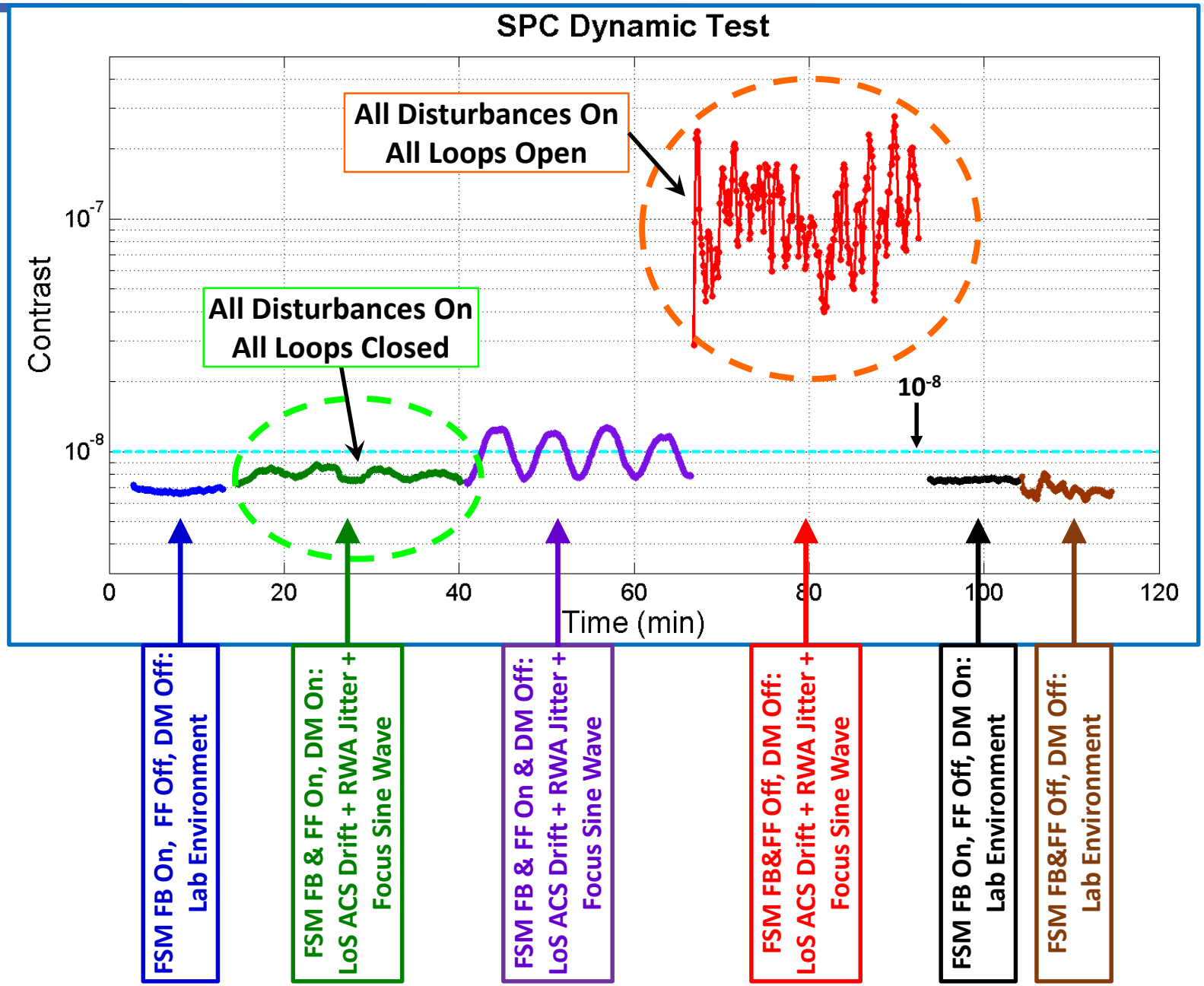


Summary of Progress Since Review

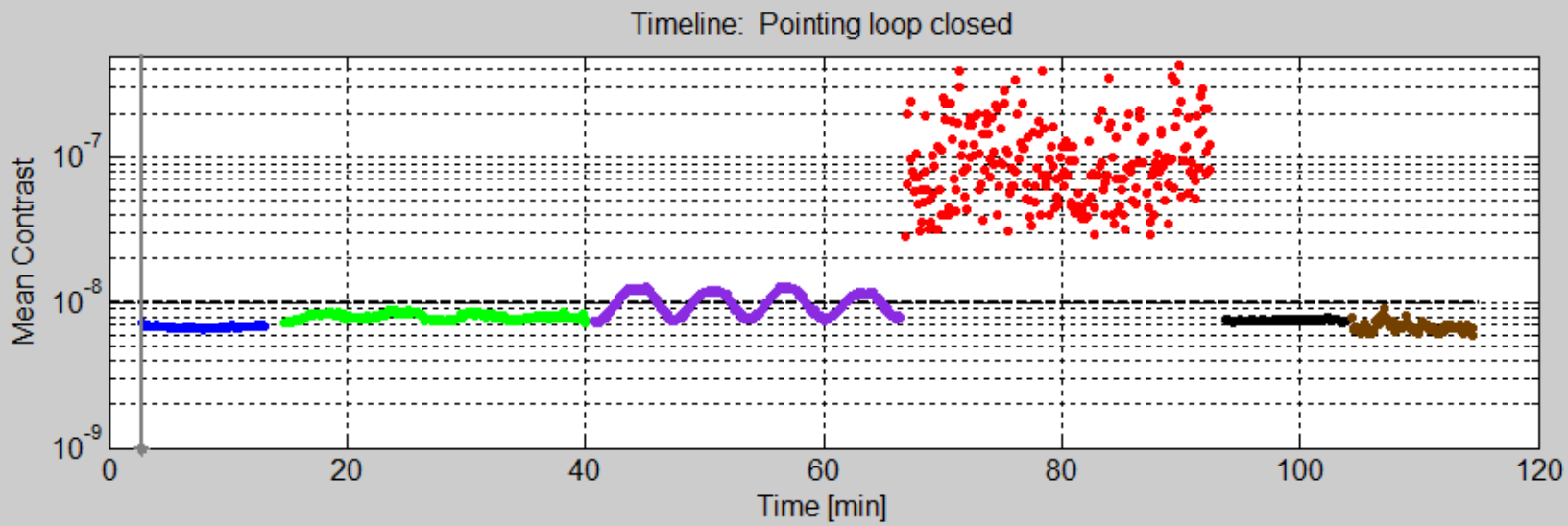
- **Static tests**
  - Further updates to the testbed pseudo-star (replaced COTS pinhole with a clean, JPL-made pinhole) greatly reduced unmodulated starlight residual.
  - Improved wavefront control algorithm approach (regularization schedule) reduced modulated starlight residual
  - In combination, these resulted in a significant improvement of static OMC contrast levels:
    - **1.6×10^{-9} for HLC static: full 360% 3-9 λ/D annulus, 10% broadband centered at 550nm**
    - **4.3×10^{-9} for SPC static: 2x65% 2.8-8.8 λ/D bowtie, 10% broadband centered at 550nm**

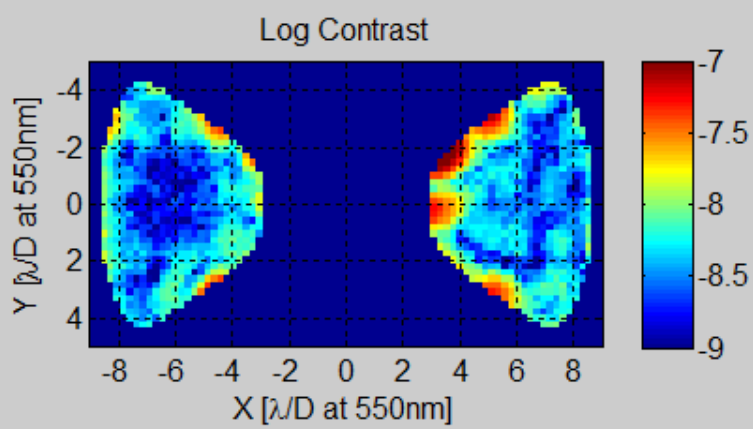
- **Dynamic tests**
  - Dynamic testing with the new front end and lower static contrast is in progress, injecting and correcting dominant on-orbit disturbances: Pointing drift/jitter and focus drift
  - **Recent results show dynamic OMC (both HLC and SPC mode) contrast better than 1×10^{-8} in presence of WFIRST flight-like dynamic disturbances and LOWFS/C correction**
  - Improved LOWFS/C robustness and performance
    - LOWFS reconstructor built from the testbed sensor response of FSM and DM
    - Better DM actuator gain calibration to reduce the DM low order WFE correction residual error
    - Sensing “pupil shear modes” reduces LOWFS sensor error from testbed non-common path drift (SPC mode)
    - Multiple ringers in feedforward control to increased the notch filter bandwidth (~0.25 Hz)
    - Feedforward to suppress the “uncooperative” frequency at ~120 Hz

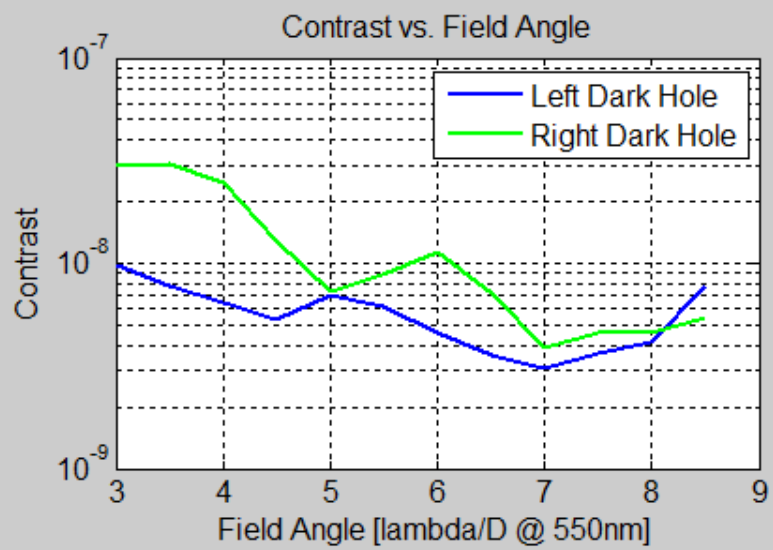
SPC+LOWFS/C Dynamic Test Result



SPC + LOWFS/C Dynamic Test: Movie



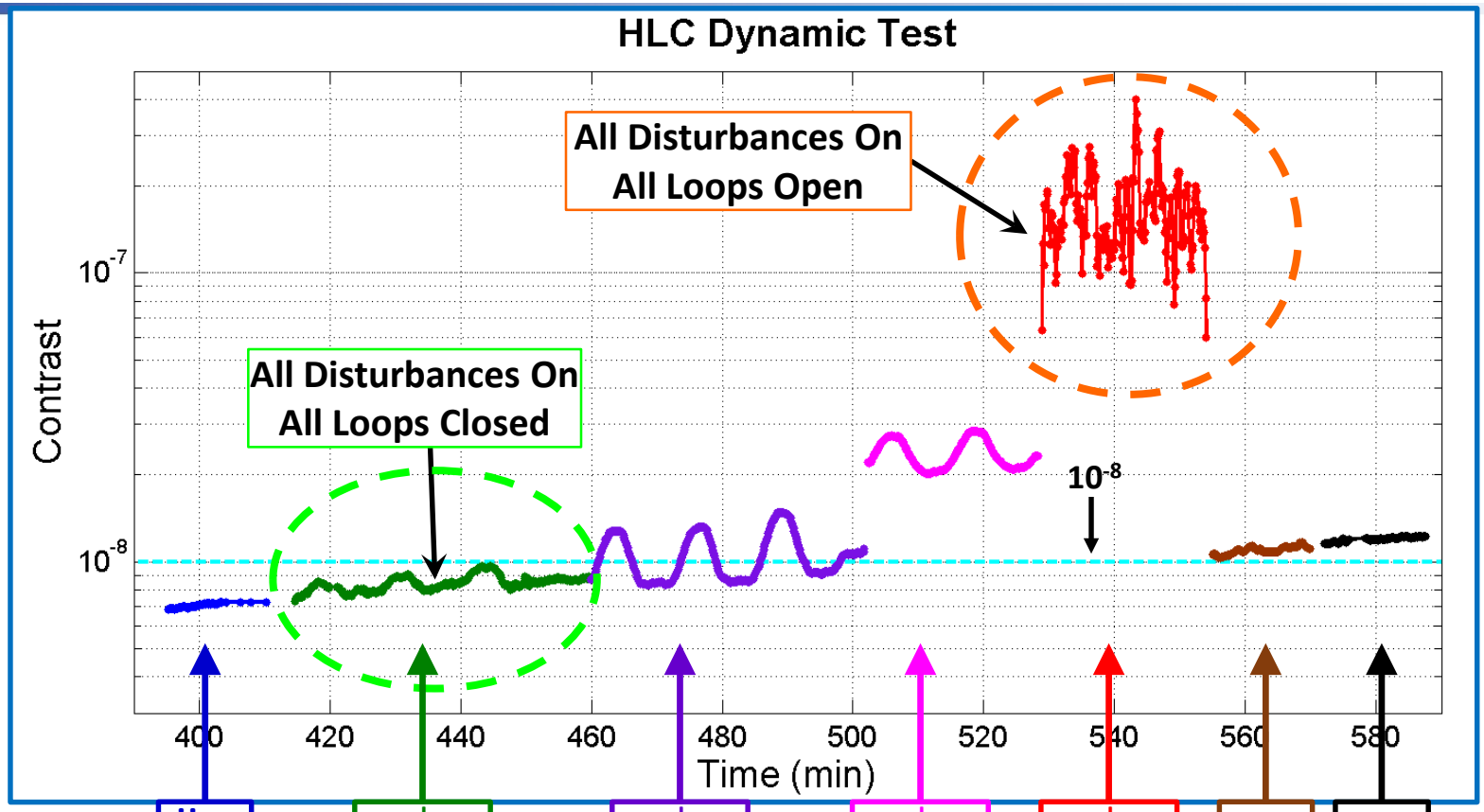




SPC+LOWFS/C Dynamic Test Result

- **SPC dynamic test demonstrating coronagraph contrast <1x10^{-8} with simulated on-orbit pointing and focus disturbances and LOWFS/C sensing & correction.**
- Coronagraph Mode: Shaped Pupil Coronagraph
  - Contrast recorded with a 10% bandwidth filter centered at 550 nm.
- Line-of-sight Error Injected: 14 mas rms drift + CBE line of sight jitter at 600 rpm wheel speed (72 harmonic tones)
  - LoS error injected by OTA Simulator's Jitter Mirror (JM)
  - LoS error corrected by OMC's Fast Steering Mirror (FSM) with both feedback and feedforward loops
- Low Order WFE Injected: 2 nm p-v focus disturbance (4x worse than expected WFIRST thermal drift)
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec. In each section of test OTA put out ~2 disturbances cycles.
  - Focus corrected by one of OMC's deformable mirrors (DM).

HLC+LOWFS/C Dynamic Test Result



FSM FB On, FF Off, DM Off: Lab Environment

FSM FB & FF On, DM On: LoS ACS Drift + RWA Jitter + Focus Sine Wave

FSM FB & FF On & DM Off: LoS ACS Drift + RWA Jitter + Focus Sine Wave

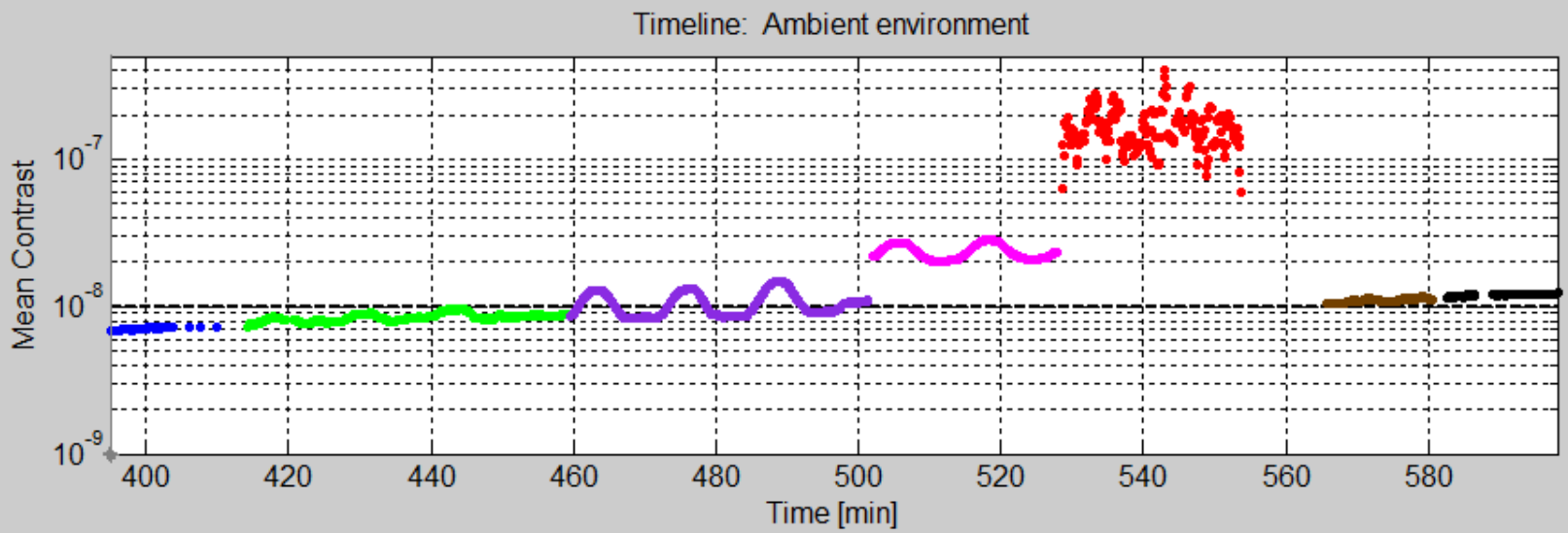
FSM FB On, FF Off, DM Off: LoS ACS Drift + RWA Jitter + Focus Sine Wave

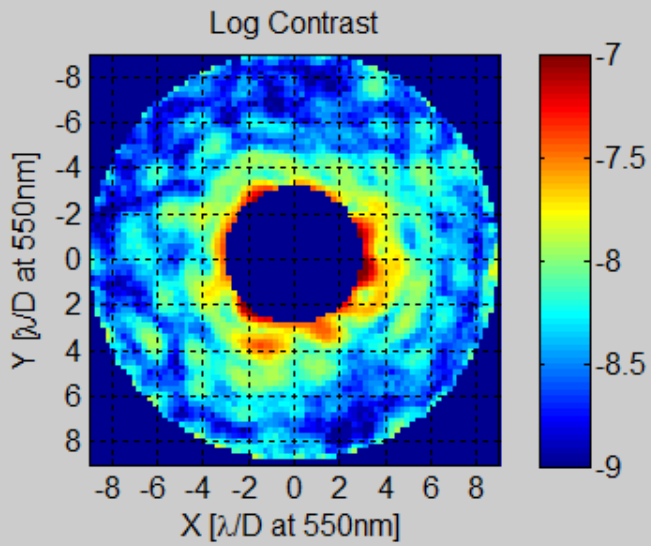
FSM FB&FF Off, DM Off: LoS ACS Drift + RWA Jitter + Focus Sine Wave

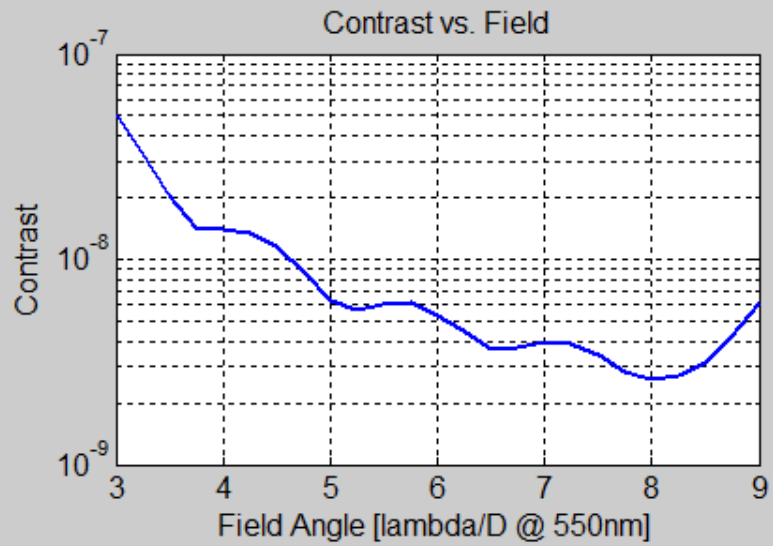
FSM FB&FF Off, DM Off: Lab Environment

FSM FB On, FF Off, DM On: Lab Environment

HLC + LOWFS/C Dynamic Test: Movie



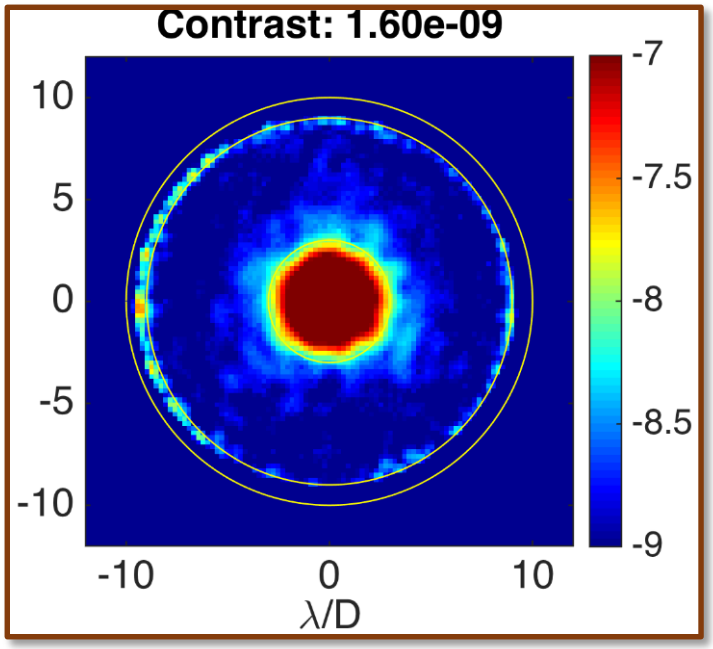


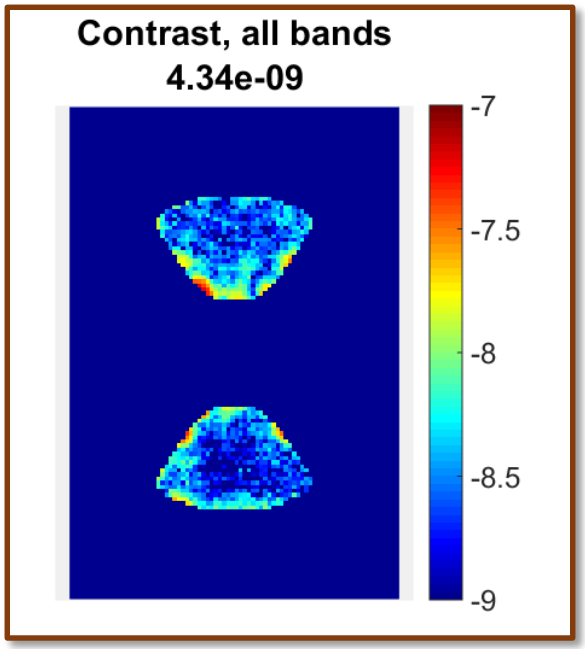


HLC+LOWFS/C Dynamic Test Result

- **HLC dynamic test demonstrating coronagraph contrast <1x10^{-8} with simulated on-orbit pointing and focus disturbances and LOWFS/C sensing & correction.**
- Coronagraph Mode: Hybrid Lyot Coronagraph
  - Contrast recorded with a 10% bandwidth filter centered at 550 nm.
  - At the start of test HLC has ~0.2nm focus bias, which made the contrast perturbation non-symmetric
- Line-of-sight Error Injected: 14 mas rms drift + CBE line of sight jitter at 600 rpm wheel speed (72 harmonic tones)
  - LoS error injected by OTA Simulator's Jitter Mirror (JM)
  - LoS error corrected by OMC's Fast Steering Mirror (FSM) with both feedback and feedforward loops
- Low Order WFE Injected: 1 nm p-v focus disturbance (2x worse than expected WFIRST thermal drift)
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec. In each section of test OTA put out ~3 disturbances cycles.
  - Focus corrected by one of OMC's deformable mirrors (DM).

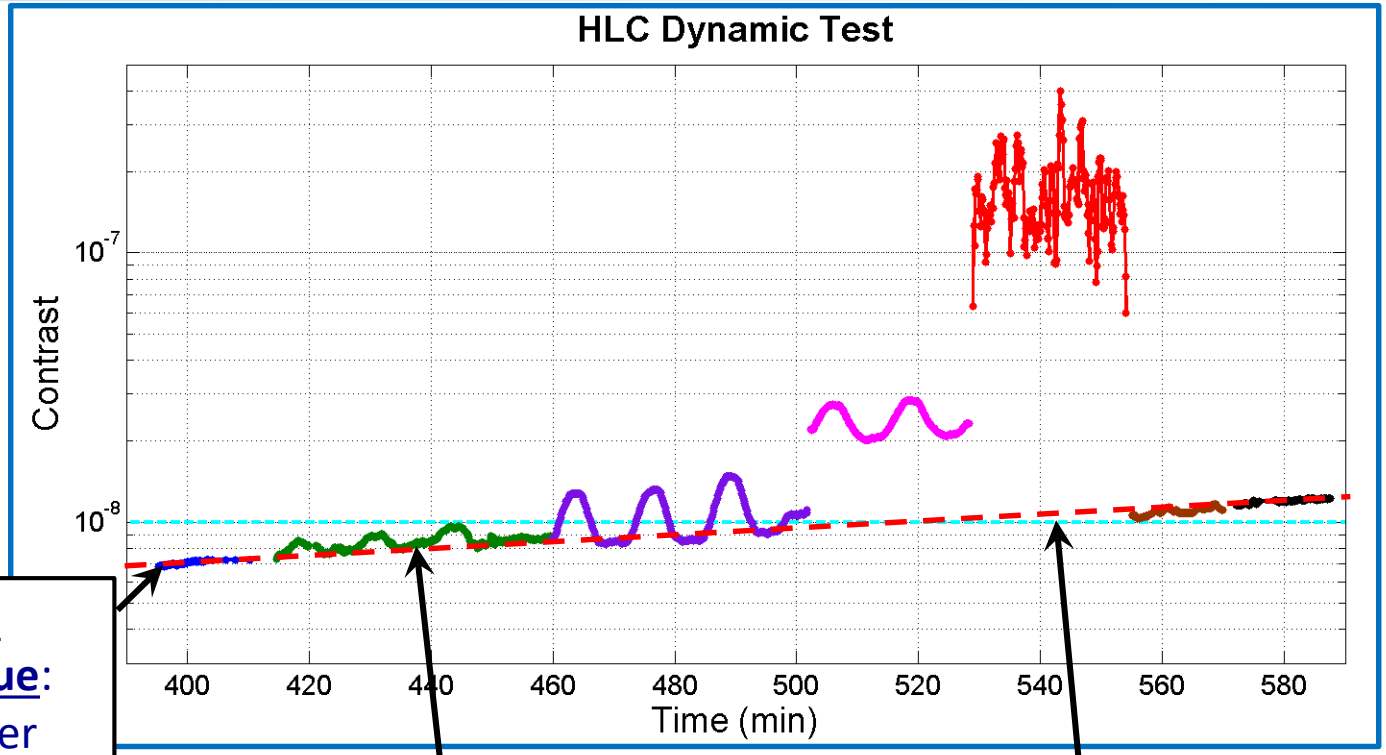
Static Contrast: HLC and SPC





- **OMC testbed static contrast has significantly improved for both HLC and SPC modes**
- **Latest contrast results (10% bandwidth at 550 nm): SPC = 4.3×10^{-9} and HLC = 1.6×10^{-9}**
  - Better wavefront control algorithm by alternating the EFC control aggressiveness (regularization).
  - Replaced the commercial metallic, laser-burnt pinhole with a pinhole made at JPL using e-beam lithography, etched in a thin silicon wafer.
  - Reduced testbed LoS jitter by turning off the strain gauges on jitter mirror and fast steering mirror (HLC)

Dynamic Test Results Discussion



Starting contrast worse than the best static value:

- Scoring with 10% filter while EFC was done with 5 uniformly weighted 2% bands -> 10% worse
- Jitter Mirror and FSM strain gauges on -> adds ~3.4e-9 contrast

Both are TB specific, not flight relevant

Focus post-correction residual contrast:

- DM gain calibration errors (recently improved, will be improved further)
- Residual focus (minor)

Testbed drift:

- Drift is sporadic and needs further exploration.
- Relevant to future low flux/long duration tests.

Summary and Future Work

Milestone 9 Results:

- Demonstrated WFIRST Occulting Mask Coronagraph $<10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.
  - Both SPC and HLC modes meet this threshold
- After testbed algorithm and hardware improvements guided by modeling, the testbed has reached the best levels of static contrast ever demonstrated with an obscured aperture.

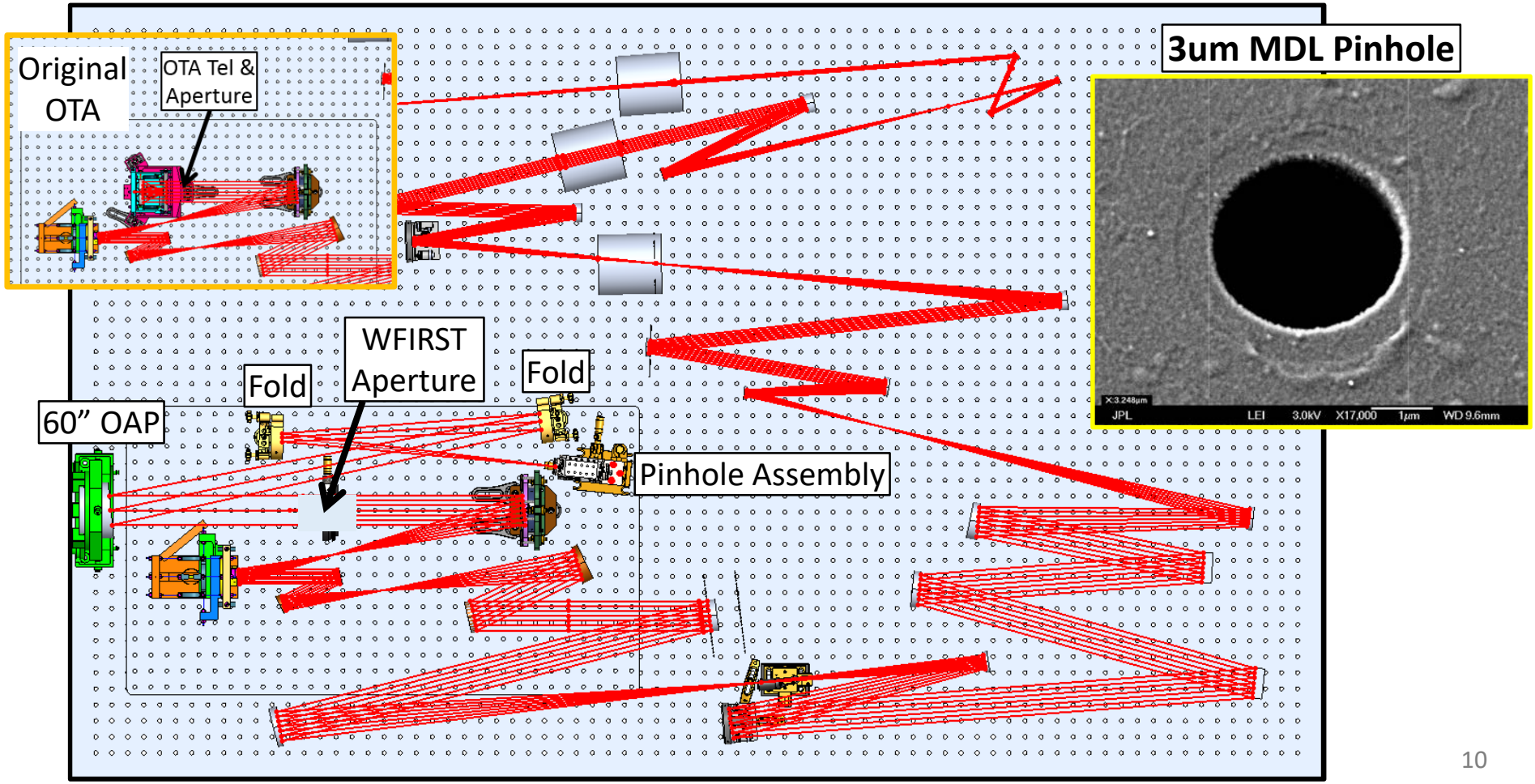
Future testbed work will focus on increasing fidelity end-to-end demonstrations on path toward TRL6:

- Broadband wavefront control using IFS data cubes
- Starlight suppression with low photon flux
- Dark hole convergence rate consistent with model predictions
- Speckle stability with LOWFS/C for post-processing
- Continue CGI+LOWFS/C testing with disturbances from the updated WFIRST jitter and thermal observatory models

Backup Slides

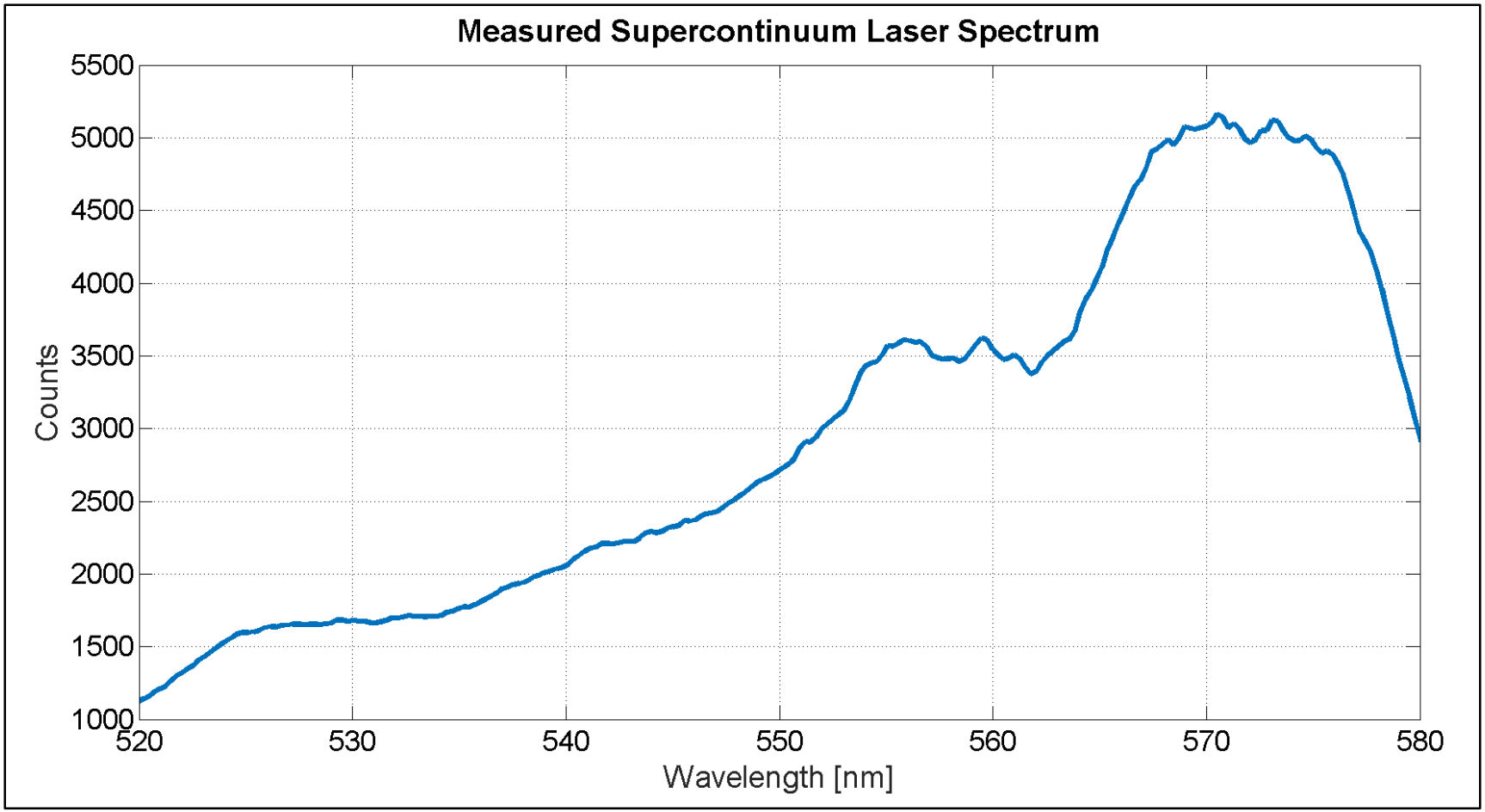
Current Modified OTA Simulator

- F/33.3 injection with 60” OAP: significantly reduced (~5X) pseudo star size
- MDL pinhole: thin, non-metallic, etched in silicon at MDL, excellent dimension and edge
- Pinhole on a stage with a linear motor for focus disturbances.
  - Scale = 1 nm RMS focus / 32 um linear motor motion
- A freestanding pupil mask in collimated beam, replacing the OTA Telescope

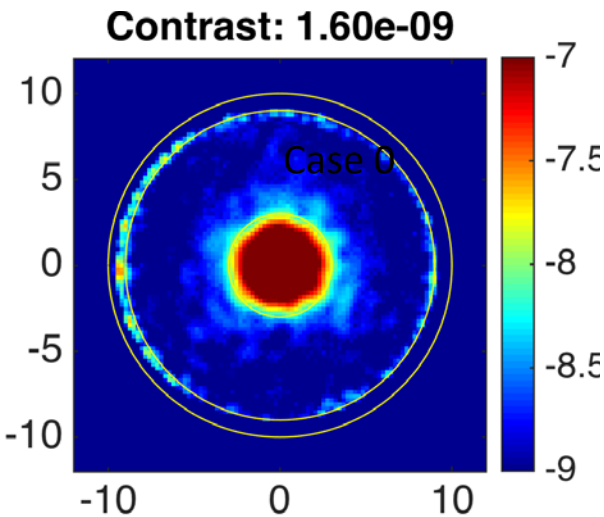


MCB SC Source Spectrum

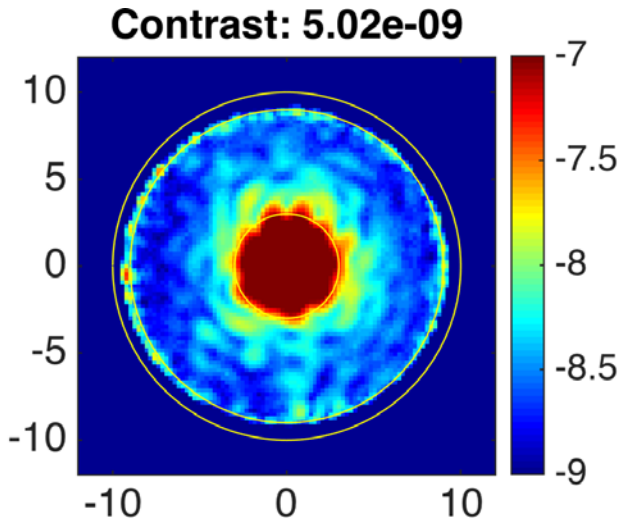
- Dynamic test scoring: 10% broadband with wavelength: 522.5 nm – 577.5 nm
  - The spectrum flux is biased toward longer wavelength
- EFC darkhole creation: Five equally weighted 2% narrowband with wavelength centered at: 528 nm, 539 nm, 550 nm, 561 nm, 572 nm



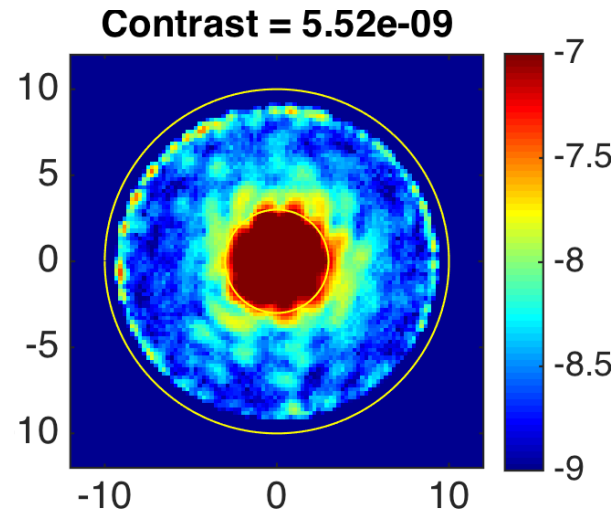
HLC Contrasts



Case A



Case B

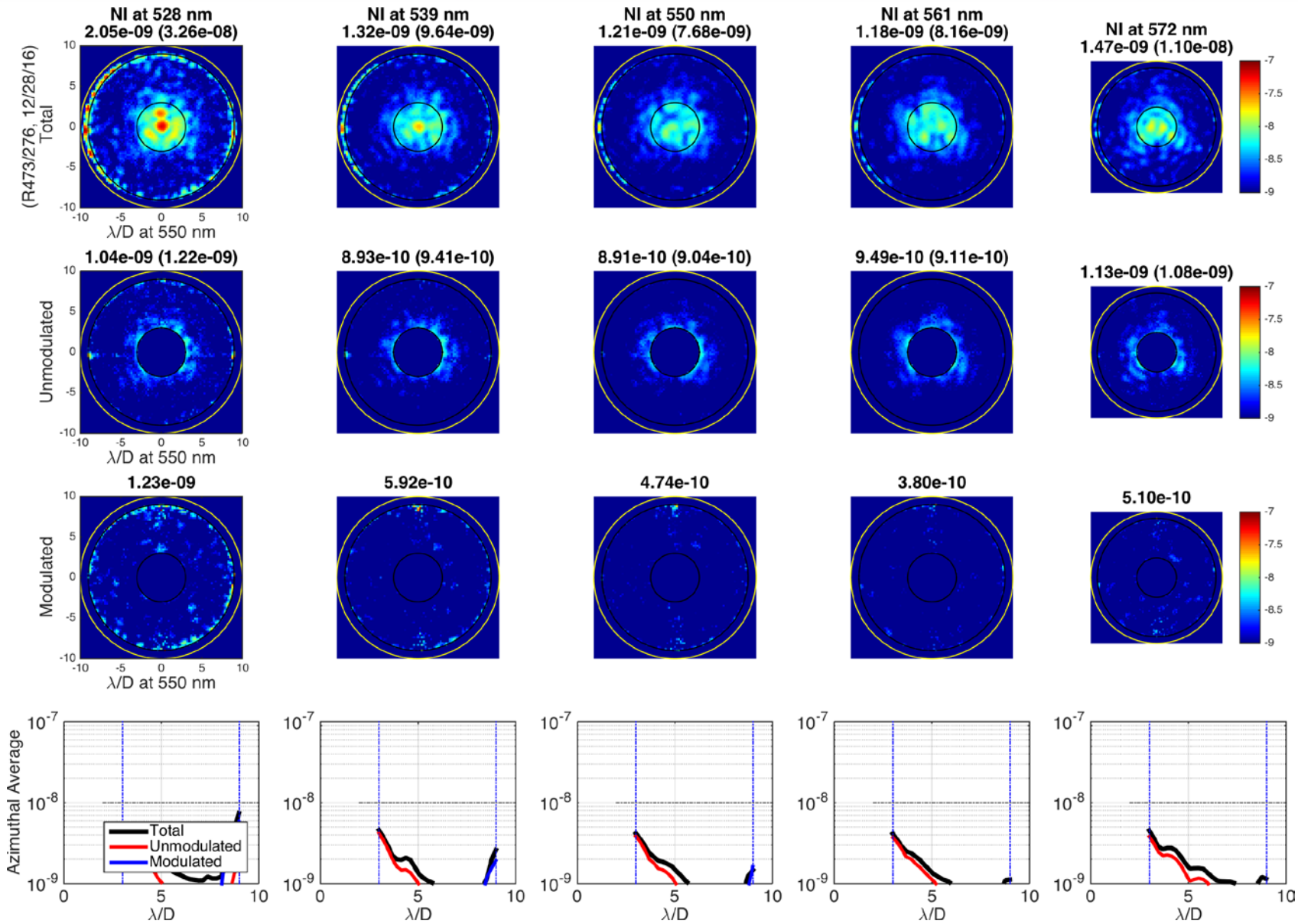


Case C*

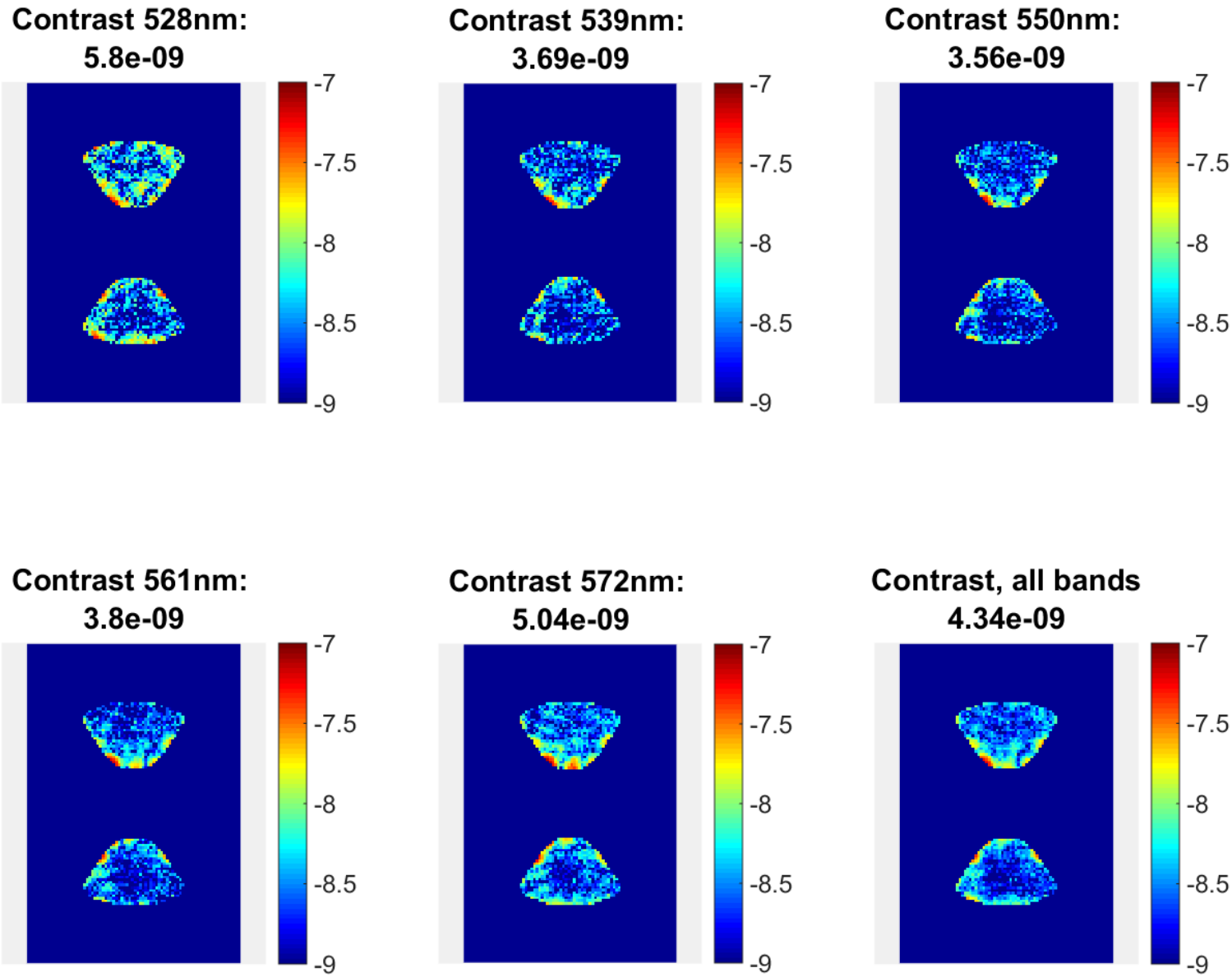
	Spectrum average	Strain Gauge	Jitter & its impact on ΔContrast estimation		Measured unmodulated	Measured Total	Note
Case A	5 λ average	OFF	0.57 mas RMS/Axis	ΔC=1.1E-9	C=9.8E-10	**C=1.6E-9**	Best Reported
Case B	5 λ average	ON	1.15 mas RMS/Axis	ΔC=4.4E-9	C=4.2E-9	**C=5.0E-9**	
Case C	10 % single shot	ON	1.15 mas RMS/Axis	ΔC=4.4E-9	N/A (no probing)	**C=5.5E-9**	Red shift of laser spectrum

*** Initial condition for dynamic test**

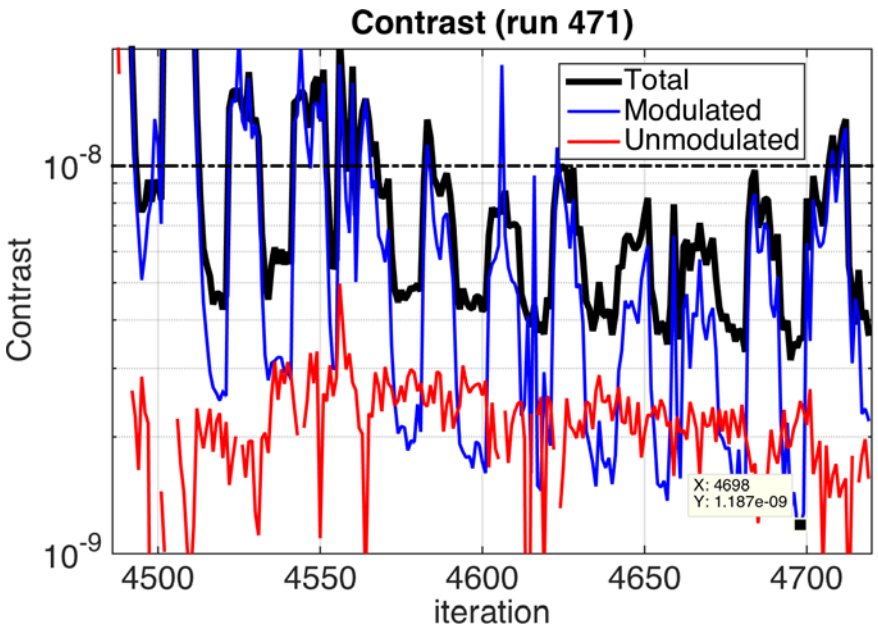
HLC Static Contrast Spectrum

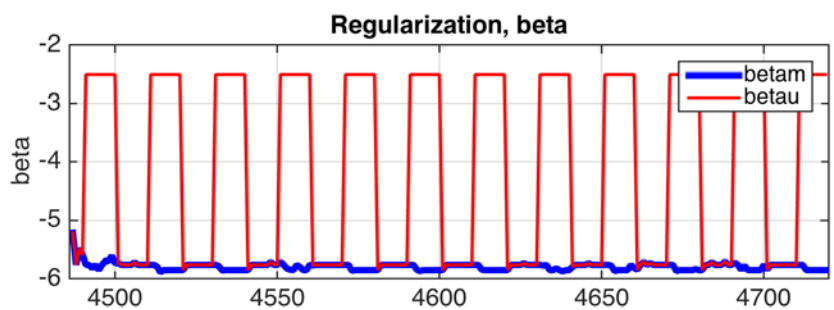


SPC Static Contrast Spectrum



Nulling Strategy Improvement



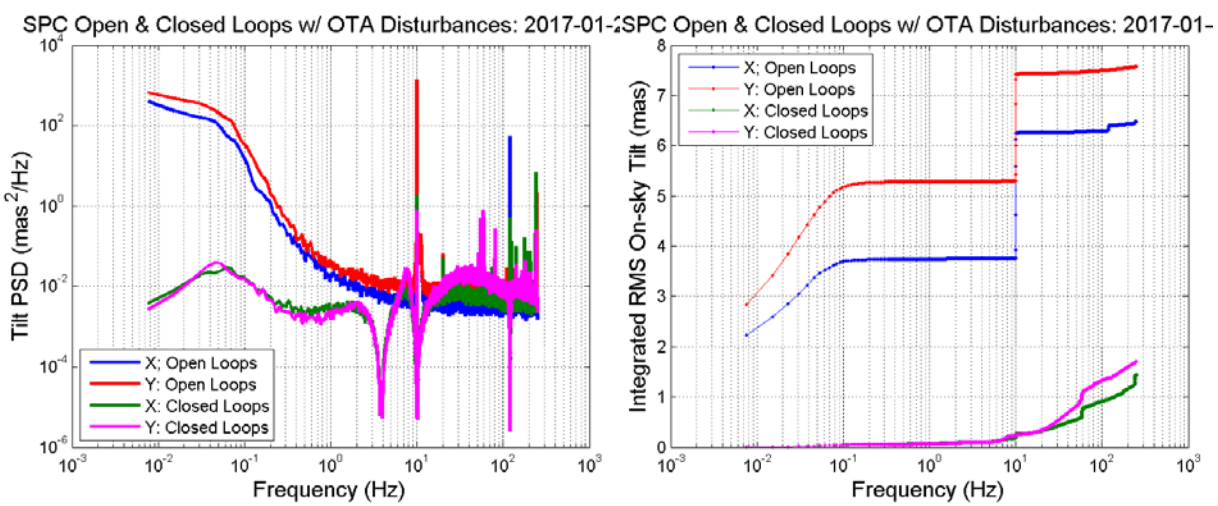


- **Control strategy improved**
  - Understand residual E in the dark hole & our control algorithm in SVD mode space
  - Observed unexpected coupling between easy and hard controllable modes.
  - Alternating aggressive and conservative regularization greatly reduces the modulated light.
  - Detailed documentation in progress
- **Automated wavefront control strategy is implemented.**

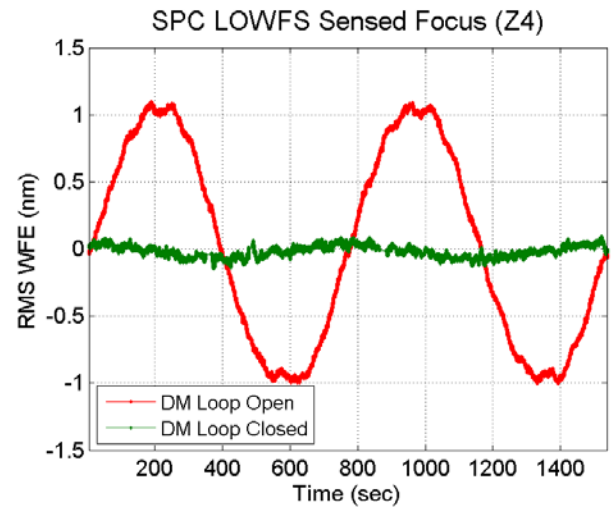
SPC Dynamic Test LOWFS Performance

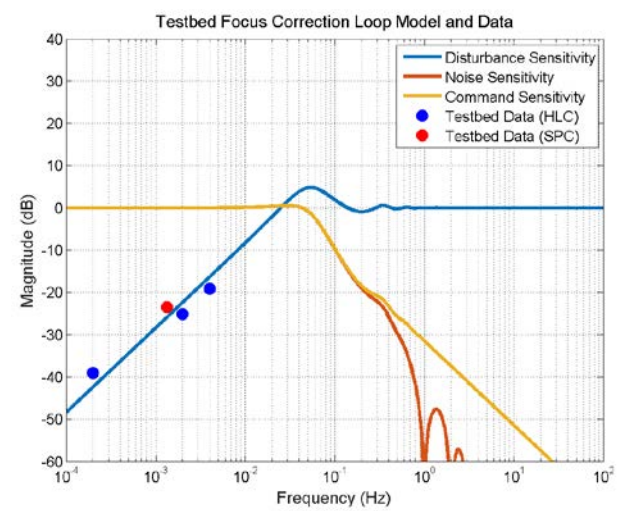
- **Open and closed error sensed by SPC LOWFS**
  - *Lower Left*: PSD of tip-tilt error converted to on-sky pointing angle (milli-arcsec).
    - The feedforward notches for RWA jitter correction at fundamental (10 Hz) and sub-harmonic (3.7 Hz) frequencies
    - The feedforward notch at lab line frequency of 120 Hz
  - *Lower Middle*: integrated WFE for LoS
  - *Upper Right*: 2 sec averaged LOWFS sensed focus error
    - Sinusoidal focus disturbance has an amplitude of +/-1 nm with period of 750 sec. The temporal change is much faster compared with WFIRST on orbit thermal drift (~10 pm/ hour). The residual focus ~+/-0.07nm.
  - *Lower Right*: Modeled focus rejection function and testbed data (HLC and SPC)

Line-of-Sight Control



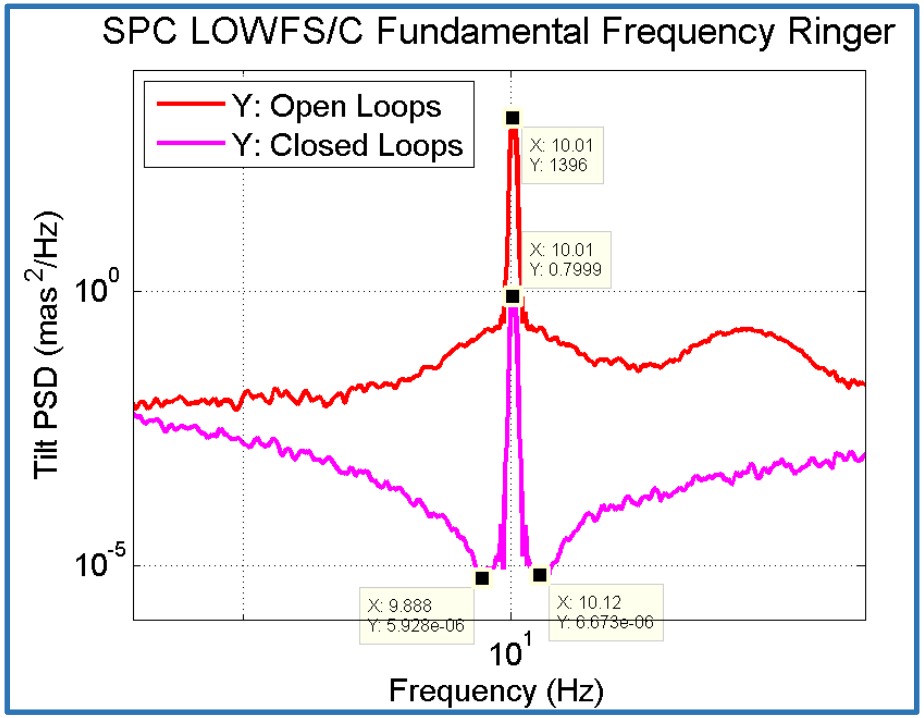
Focus Control

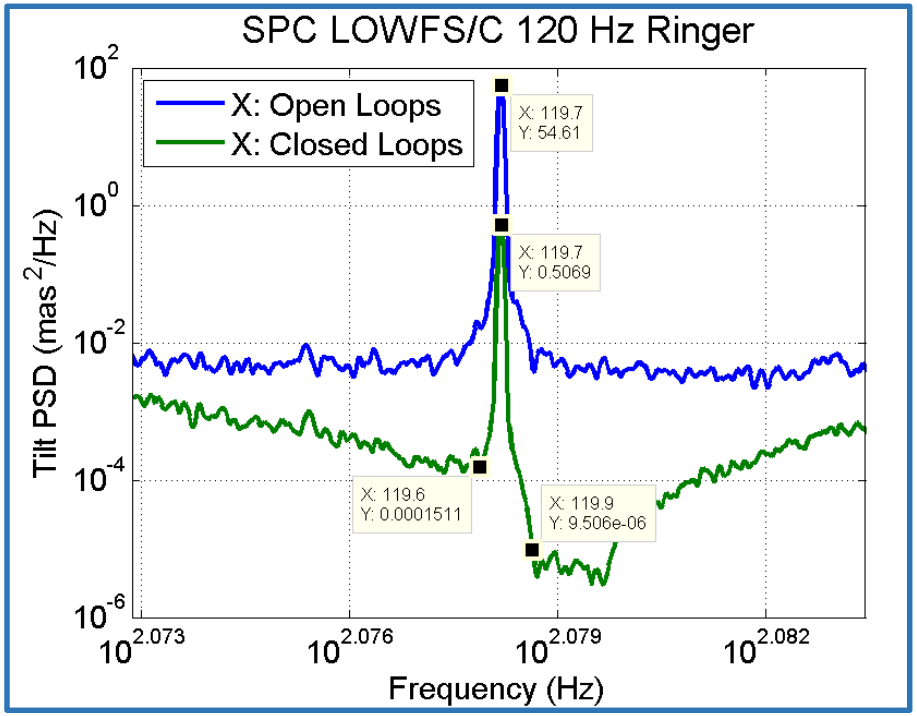




SPC Dynamic Test LOWFS Performance

- **Multiple ringers to increase the robustness of feed forward control (*lower left*)**
  - Detailed open and closed loop PSD near fundamental frequency for jitter from RW at 600rpm (10 Hz)
  - Multiple ringers added to increase the notch filter bandwidth to ~0.25 Hz.
  - Feed forward control suppressed the fundamental jitter energy by 30 dB
- **Feed forward control to suppress the 120 Hz lab noise (*lower right*)**
  - Lab noise from AC system inside 318-Highbay.
  - Frequency is uncooperative and wondering around 120 Hz.
  - Adding multiple ringers to suppress the "wondering" 120 Hz lab noise by 10 dB

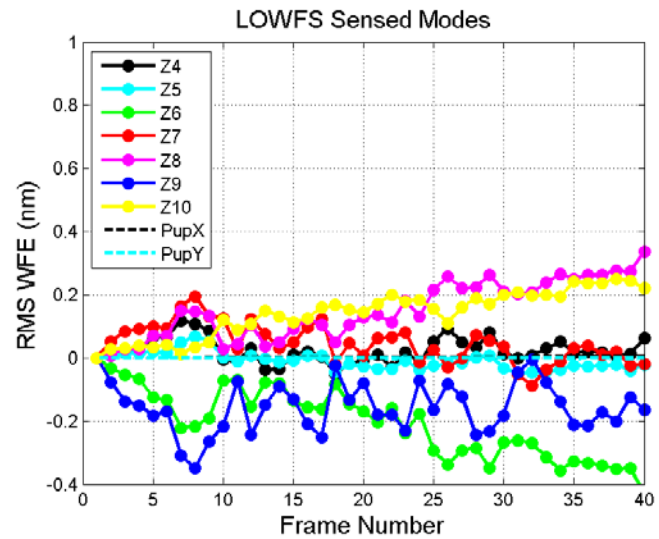




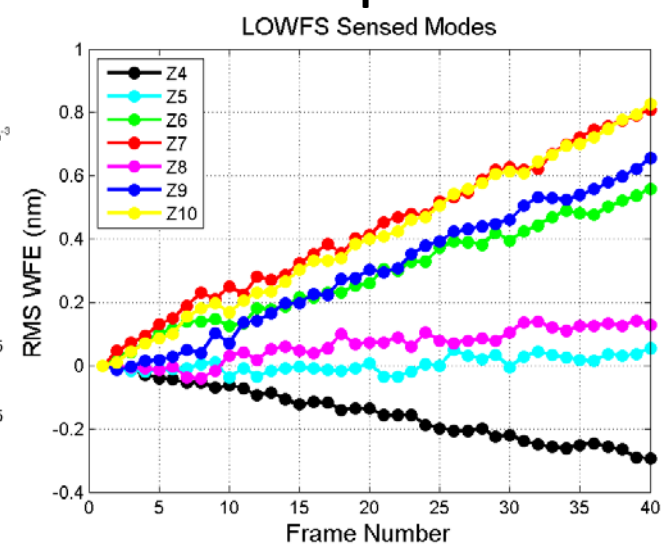
SPC LOWFS: Sensing Pupil Shear Mode

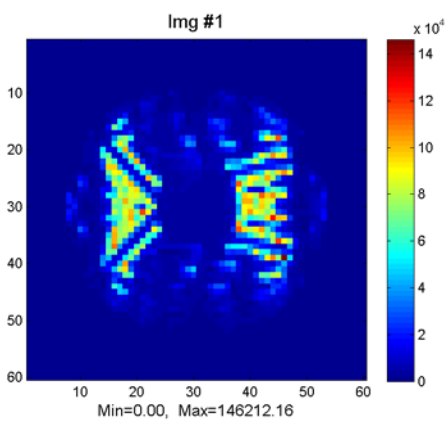
- The sharpness of SPC LOWFS image (*lower left*) makes it sensitive to the pupil image shear between the reference image and the signal images
- The thermal variation in the testbed in the LOWFS optics and LOWFS camera can cause LOWFS image shear up to 0.07 pix/hour
- Without sensing these pupil shear modes the pupil shear will cause erroneous measurement of low order wavefront errors, as shown in the *lower right* plot
- Added two pupil shear modes (*lower middle*) to the LOWFS reconstructor and re-process the same data results in correct LOWFS measurement, as shown the *upper right* plot.

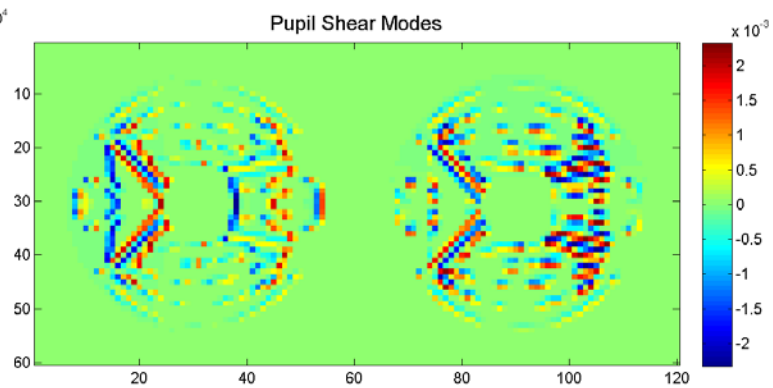
New: With Pupil Shear Mode



Old: Without Pupil Shear Mode

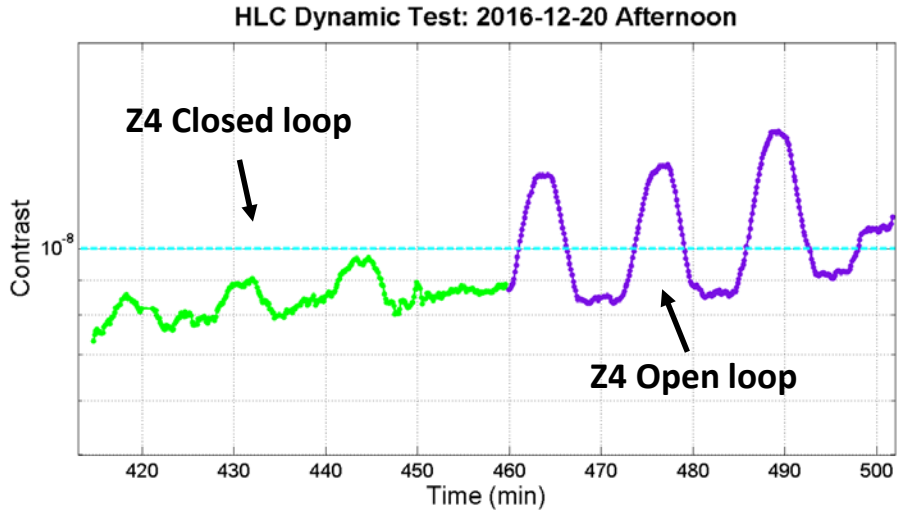




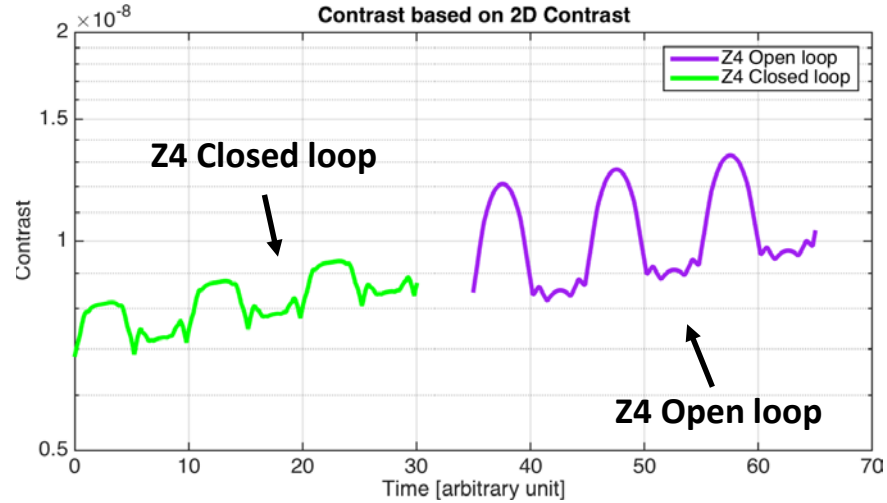


Defocus Closed-Loop Residual

Dynamic Test Result (zoomed)



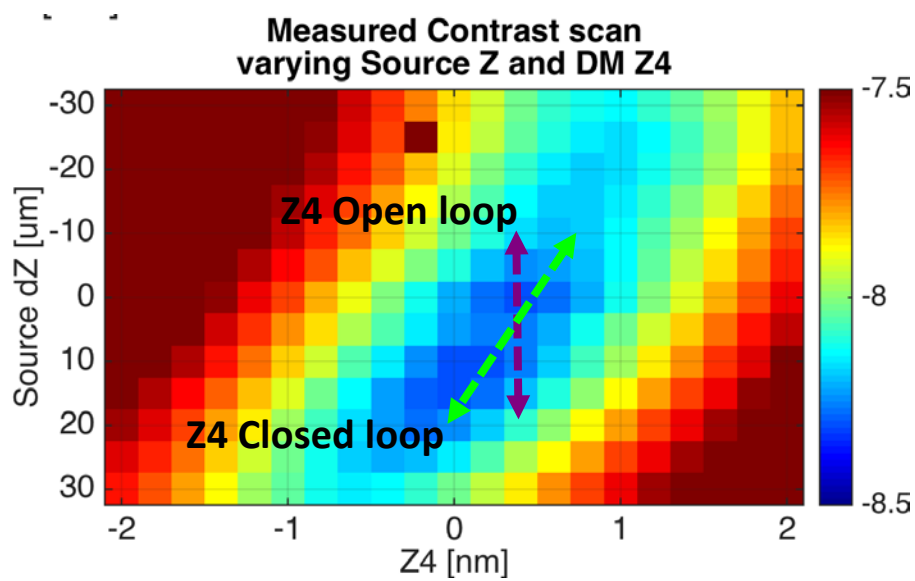
*Simulation based on NI Scan**



** Contrast drift is fitted and added.*

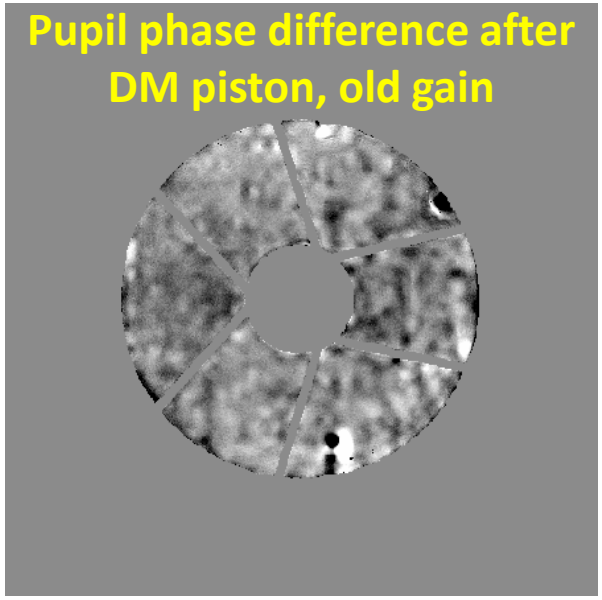
Contrast residual in the dynamic test result

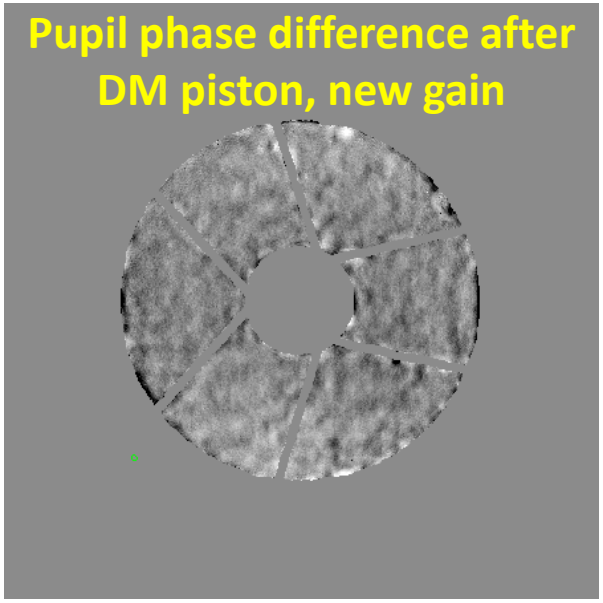
- We vary two parameters (source z-position and DM Z4) to scan contrast, and then simulate closed/open loop contrast performance.
- The mismatch between source z and DM Z4 predicts the observed closed loop residual



Understanding SPC Dynamic Results

- **~25% focus correction contrast residual remains.**
- **Most likely source: DM gain map**
  - We believe this as earlier SPC/LOWFS tests with an older gain map had much higher residuals





- **Further iteration should improve this (edges and struts in particular)**
- **Also, need to see how it changes with local voltage (different SPC/HLC gain maps required?)**

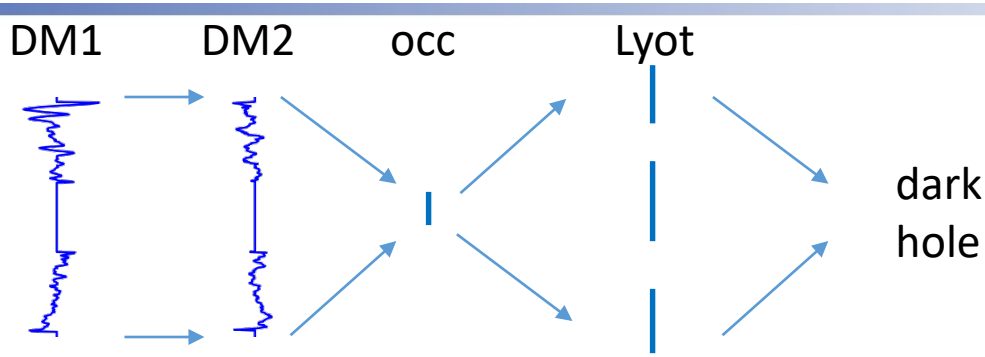
Understand HLC Dynamic Test Residuals: Summary of Error Magnitudes

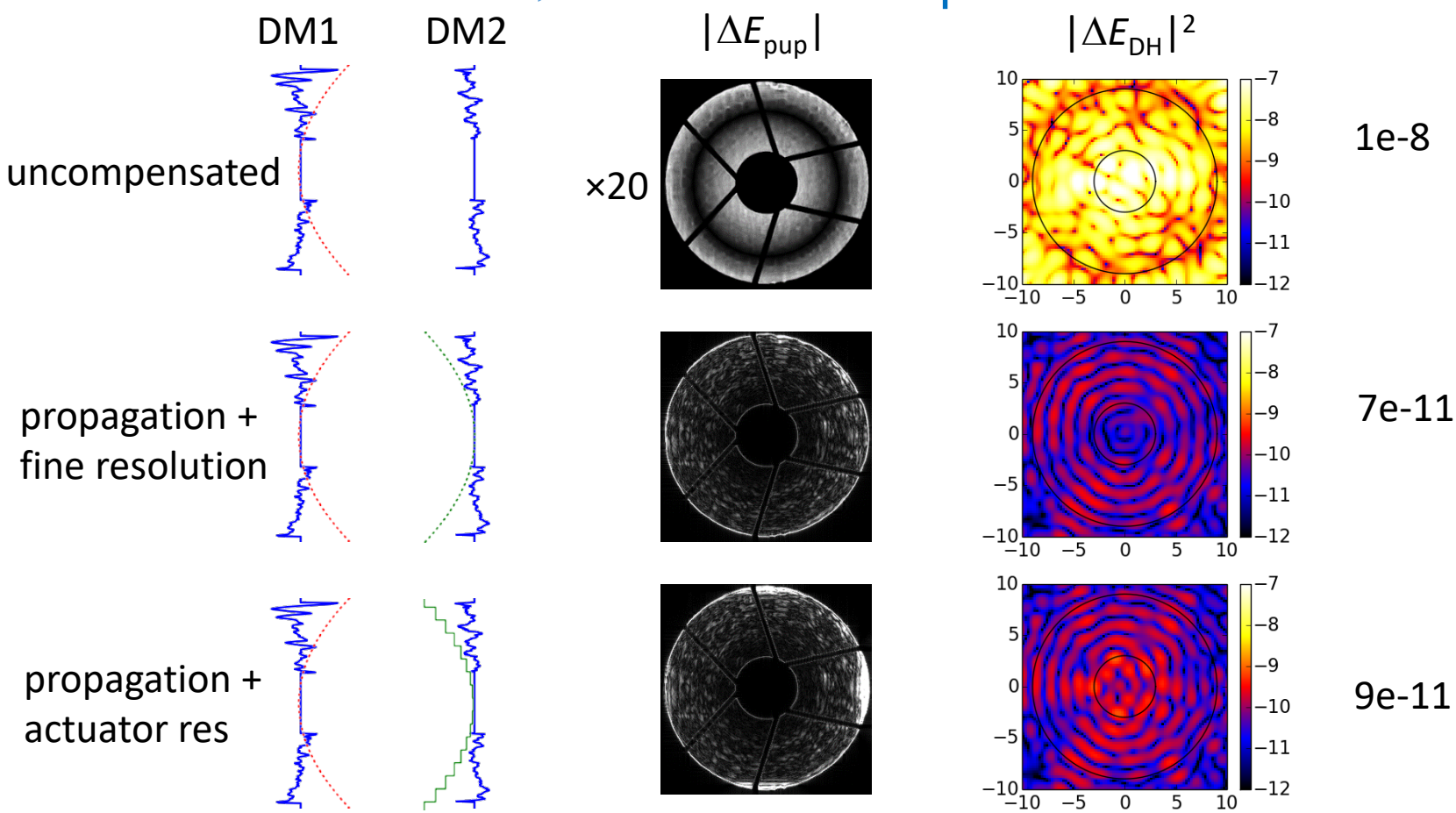
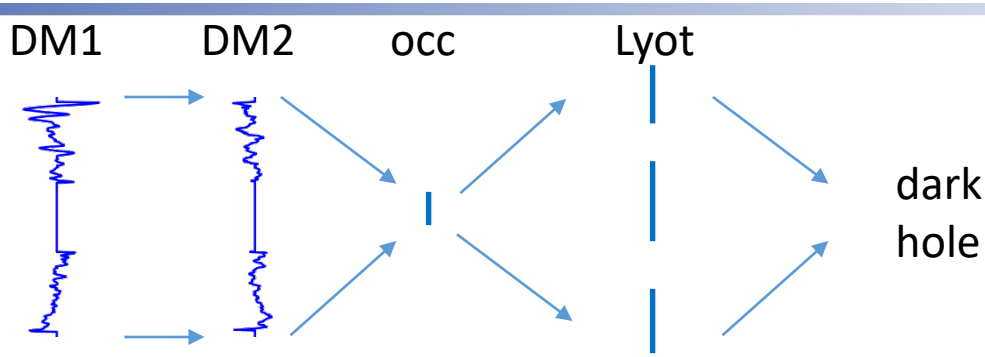
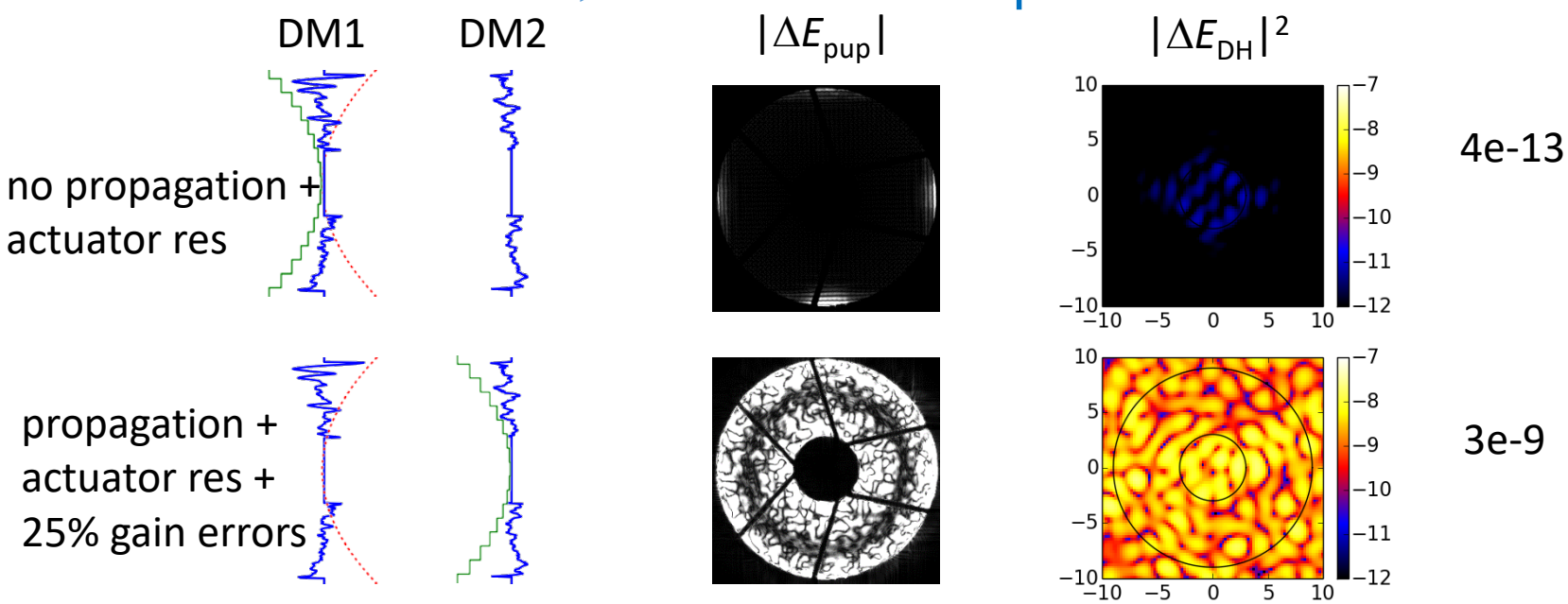
- DM Z4 application does not produce pure pupil-plane wavefront Z4 for several reasons, can they account for size of residuals at ~ 30% of open-loop $|\Delta E|^2$?
  - Finite spacing of actuator centers ("fitting error")
  - Propagation from pupil to DM2
  - HLC DM1 + DM2 shapes distort pupil Z4
  - Edge effects in choice of DM voltage maps
  - DM gain calibration error produces high-order WFE modes
- The only effect that matches observed residuals is 25% rms DM actuator gain errors
  - Gain error estimate is ~ 8% rms

	$<\|\Delta E\|^2>$
1 nm pupil Z4 pix-by-pix	1.0e–8
1 nm pupil Z4 pix-by-pix – 1 nm DM2 obscuration-truncated Z4 actuators	1.5e–9
1 nm pupil Z4 pix-by-pix – 1 nm pupil Z4 pix-by-pix after DM	6e–11
1 nm pupil Z4 pix-by-pix – 1 nm +1000mm Z4 pix-by-pix after DM	7e–11
1 nm pupil Z4 pix-by-pix – 1 nm +1000 mm Z4 pix-by-pix before DM	5e–12
1 nm pupil Z4 pix-by-pix – 1 nm DM1 full-DM z4 actuators	4e–13
1 nm pupil Z4 pix-by-pix – 1 nm DM2 full-DM Z4 actuators	9e–11
DM2 25% rms actuator gain errors	3e-9

matches 30% of 1e-8 residuals, but gain errors ~ 8% rms

HLC DM correction models (1 of 2)





HLC DM correction models (2 of 2)