Hybrid Lyot Coronagraph for WFIRST:

High Contrast Broadband Testbed Demonstration

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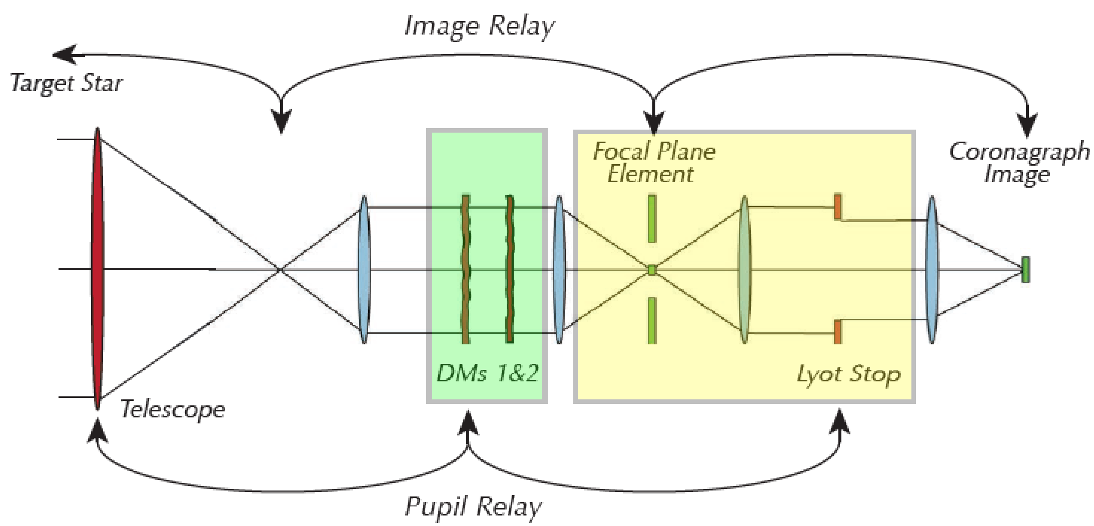
Outline

- Hybrid Lyot Coronagraph overview
- Dynamic Occulting Mask Coronagraph (OMC) testbed overview
- Dynamic test setup
- Dynamic test result
- Summary & Future works

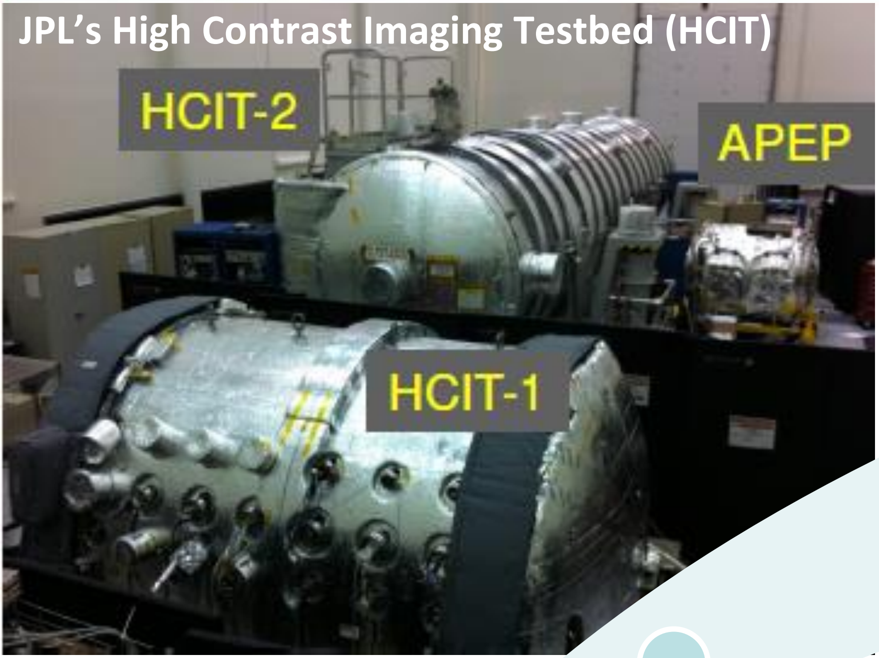
Hybrid Lyot Coronagraph Overview

Essential elements of the Lyot coronagraph



- **HLC is one of two coronagraph technologies forming the baseline WFIRST Occulting Mask Coronagraph (OMC) architecture**
  - **Responsible for planet discovery in the current Design Reference Mission (DRM)**
- **WFIRST Hybrid Lyot coronagraph essential elements:**
  - 2 deformable mirrors
  - Focal plane occulting mask
  - Lyot stop

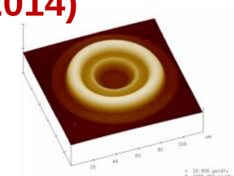
Brief History of WFIRST HLC Testbed Activity



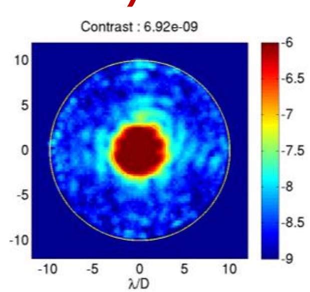
Coronagraph is added to WFIRST mission. (2013)

Hybrid Lyot occulting mask fabricated and characterized

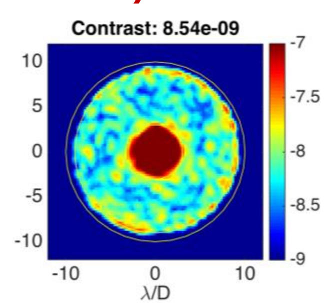
(2014)



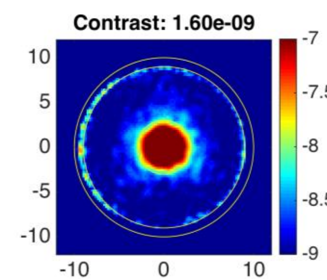
Narrowband 360° HLC contrast demonstrated with WFIRST pupil and 2 DMs (2015, 6.92x10^{-9}@ 550nm, 3-9 λ/D in HCIT2)



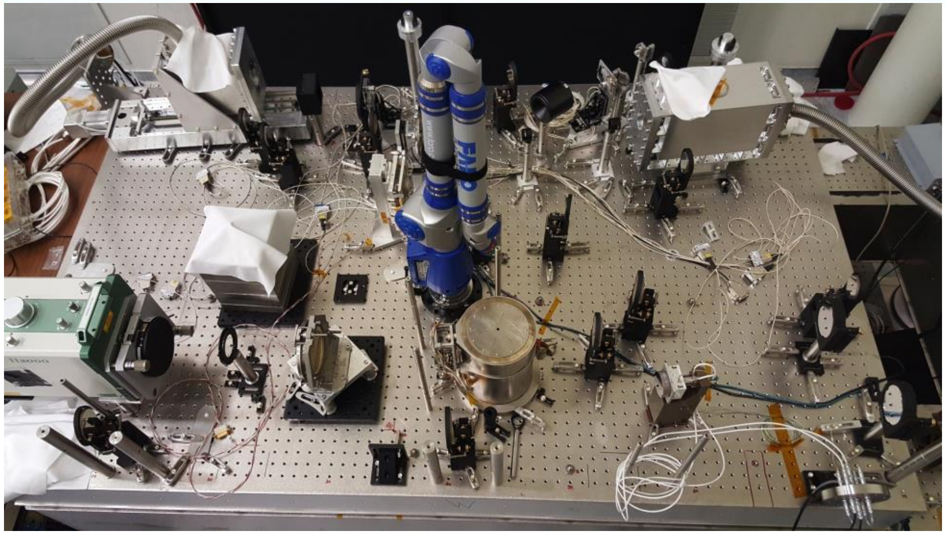
Broadband (10%) HLC contrast demonstrated (2015, 8.54x10^{-9}@ 550nm, 3-9 λ/D in HCIT2)

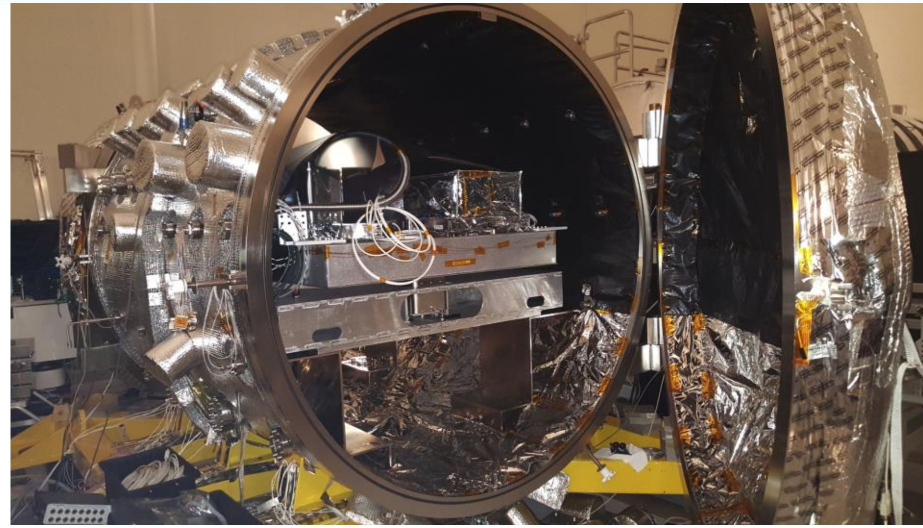


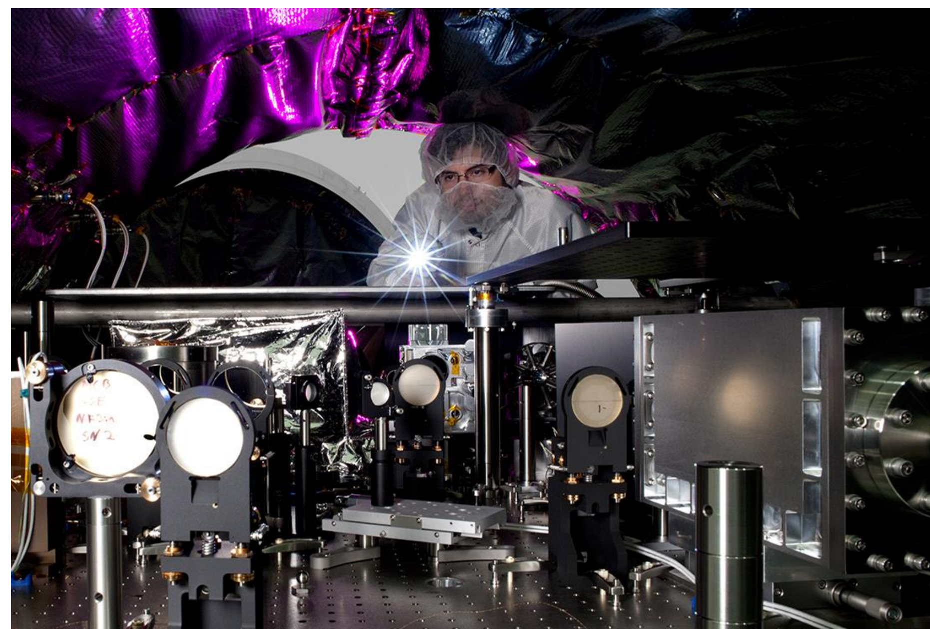
Broadband (10%) HLC contrast demonstrated in dynamic OMC testbed & model validation (2017, 1.60x10^{-9}@ 550nm, 3-9 λ/D in HCIT1)



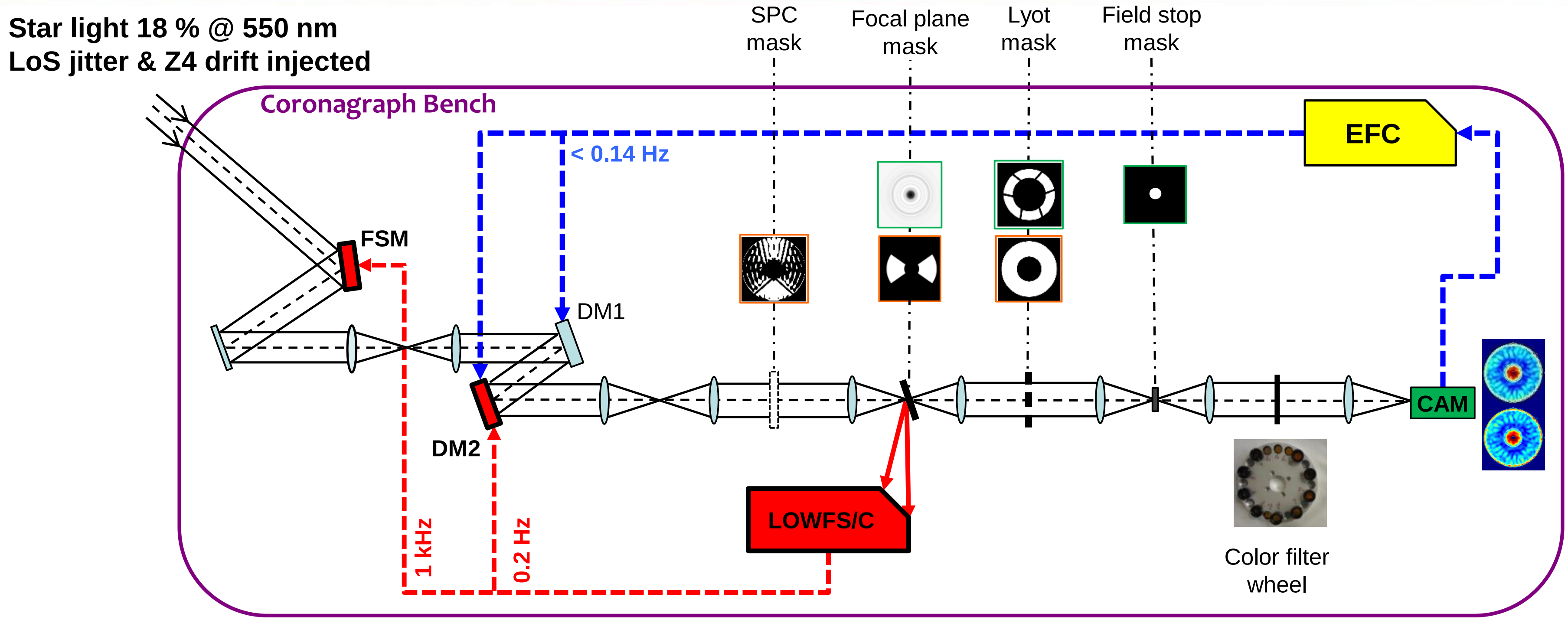
Dynamic OMC Testbed





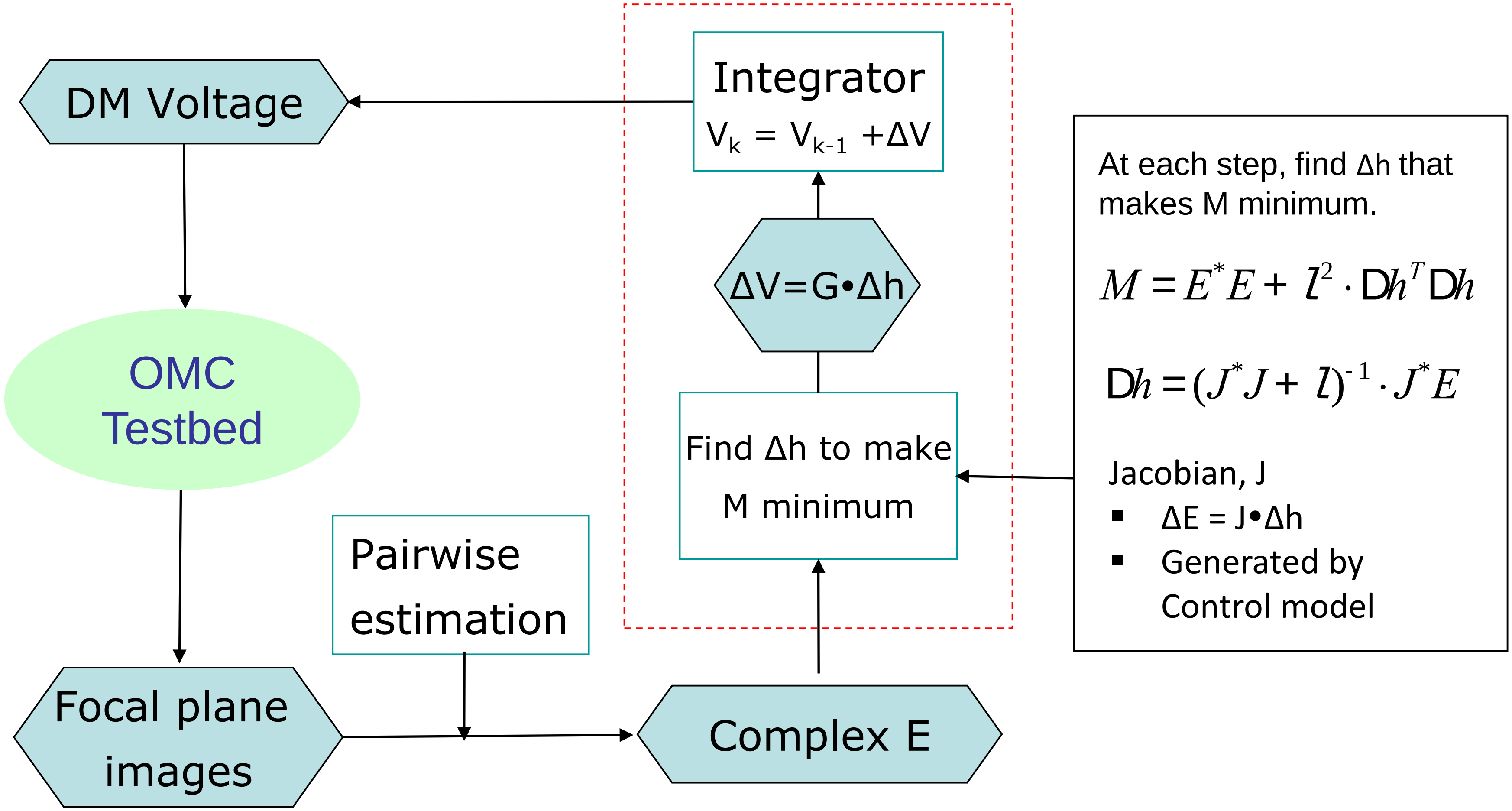


Dynamic Test Setup



- Inject WFIRST-Like perturbed star light:
  - Broadband Star (18% @ 550 nm)
  - LoS jitter (~20 masRMS) + Z4 WFE Drift (± 1 nm sinusoidal 1 hour period) + TB drift & jitter
- Three Control Loops :
  - LOWFS LoS loop closed all the time with refresh rate of 1 KHz.
  - LOWFS DM loop closed most of time with refresh rate of 5 seconds.
  - EFC DM loop with refresh rate of 7 seconds.

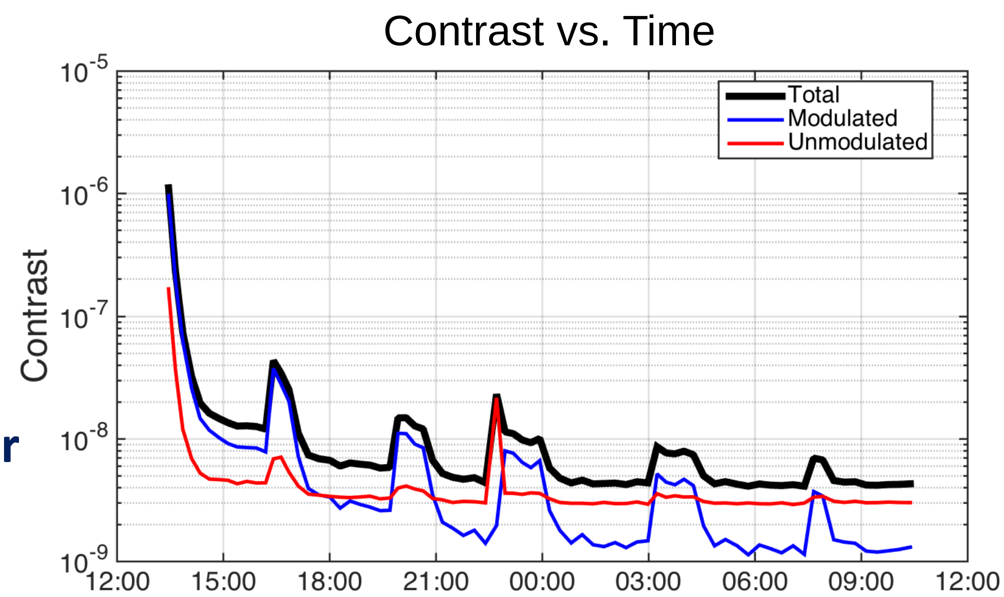
Electric Field Conjugation (EFC) Algorithm

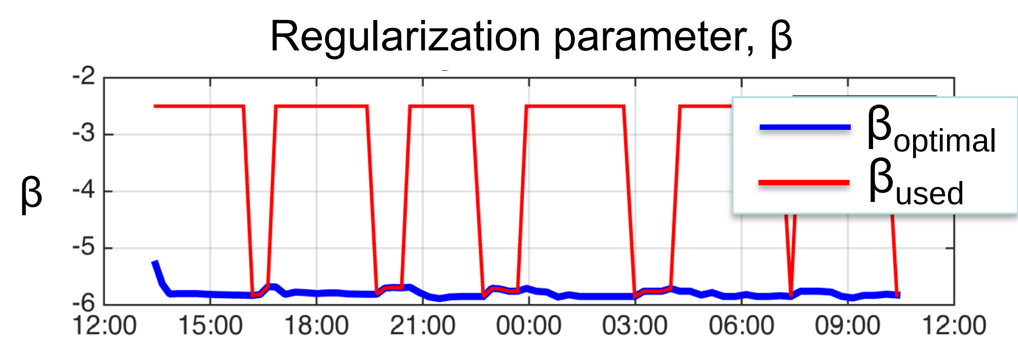


- **EFC is a gradient-descent algorithm to minimize both the complex E field and DM stroke usage with a weight, $\lambda=10^{\beta}$.**
- **"β scheduling" improves final performance and operation robustness. See SPIE-10400-23 & SPIE-10400-74.**

Dynamic Test Result (1/2)

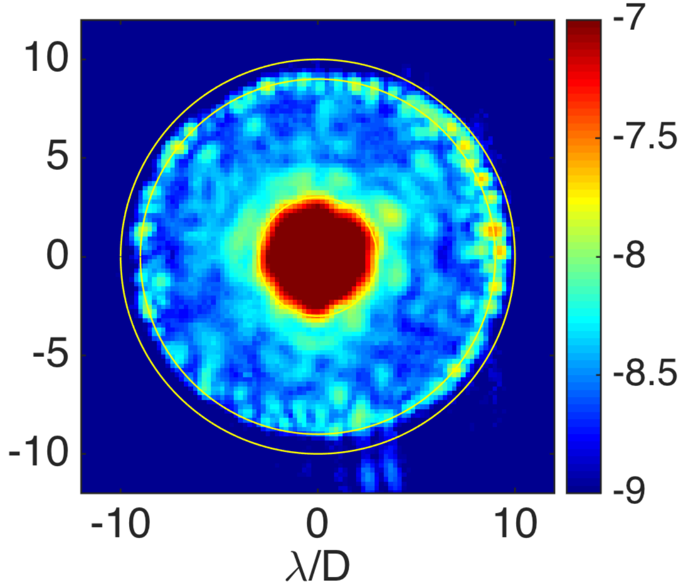
- **Additional Test Configuration:**
  - **Starting from an existing 1E-6 level DM solution.**
  - **Control is done with the "β scheduling" with no human interaction.**
  - **Three 2% BW colors are used for control/report centered at 530, 550, 570 nm.**
- **Result Summary:**
  - **Contrast (black curve) is converging to 4.44E-9, which is comparable to when no perturbation is injected.**
  - **This demonstrates high contrast generation in the dynamic environment.**

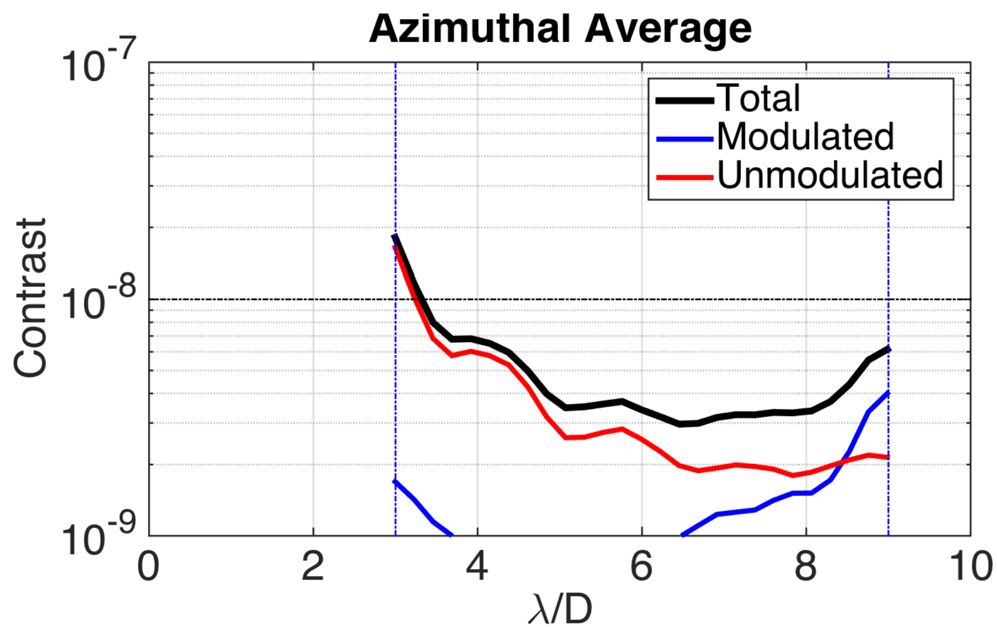




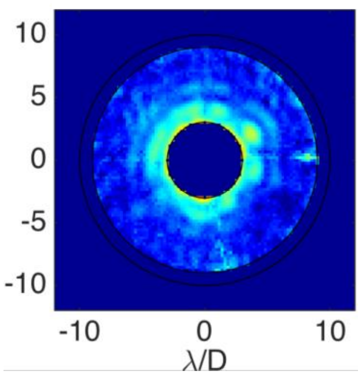
Dynamic Test Result (2/2)

Contrast: 4.44E-9

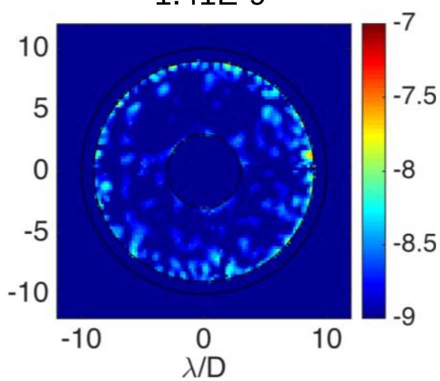




Unmodulated light
3.03E-9



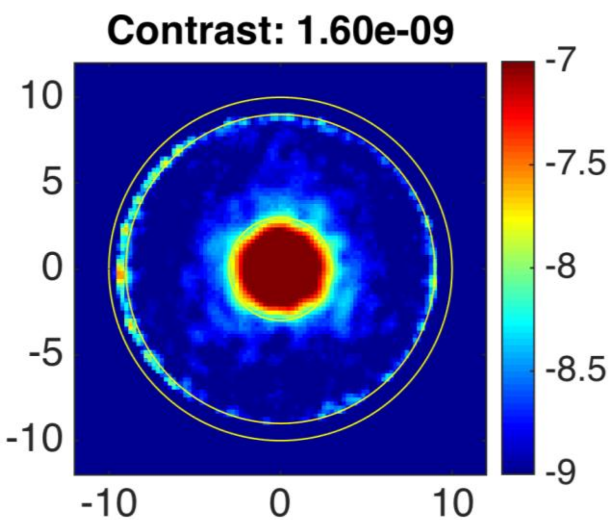
Modulated light
1.41E-9



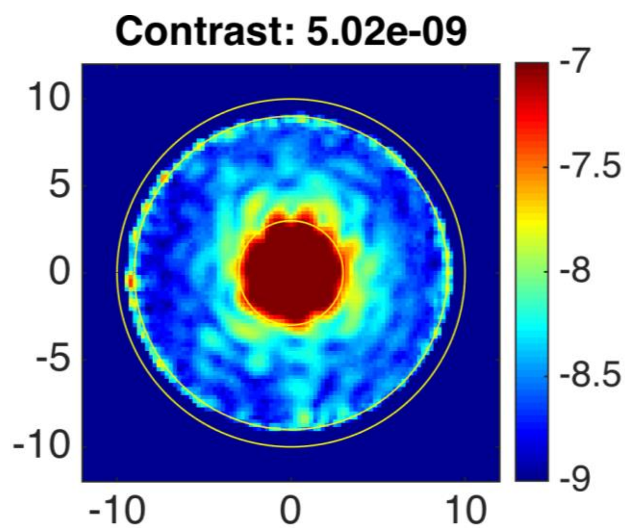
- **Contrast consisted of two terms:**
  - **Unmodulated light dominated by the LoS Jitter.**
  - **Modulated light dominated by calibration error.**

Static Testbed Results

Case A



Case B



	Strain Gauge	Jitter measured & its impact on ΔContrast estimation		Measured unmodulated	Measured Total
Case A	OFF	0.57 mas RMS/Axis	ΔC=9.75E-10	C=9.04E-10	**C=1.60E-9**
Case B	ON	1.15 mas RMS/Axis	ΔC=4.11E-9	C=4.20E-9	**C=5.02E-9**

The dominant LoS jitter impact can be estimated from Jitter and Jitter sensitivity measurement.

Contrast Breakdown

when 0.56 masRMS/Axis is measured.

Testbed Performance						**1.60E-09**
Bottom-Up prediction						**1.62E-09**
Error Terms		CBE		Sensitivity		
		value	unit	value	unit	
Statics - Modulated light						
M1	Mis-Alignment & Mis-Fabrication					3.09E-10
M2	Mis-Calibration					2.31E-10
Dynamics (< 20 minutes) - Unmodulated light						
U1	Tip/Tilt Jiitter	0.56	masRMS WFIRST Sky per Axis	3.11E-09	per masRMS^2 for both axis	9.75E-10
U2	Focus Jitter	0.02	nmRMS WFE defocus	7.01E-09	per 1 nmRMS^2 WFE focus	2.80E-12
U3	High order Jitter	0.01	nmRMS WFE	1.00E-07	per 1 nmRMS^2 WFE	1.00E-11
U4	DM Statibility	1.00	ΔmK	1.43E-11	per ΔmK^2	1.43E-11
Misc. Unmodulated light						
U5	Polarization	0.20	nmRMS WFE Ast	4.00E-10	per 1 nmRMS^2 WFE Ast	1.60E-11
U6	Occulter ghost	0.30%	AR-coating	2.00E-06		1.80E-11
U7	CMOS ghost	1.00E-07	Maximum on CMOS	1.00E-05	Ratio to maximum	1.00E-12
U8	Pseudo-Star Illumination					<1.00E-12
U9	Estimation error	3.0%	Ratio to total			4.80E-11
U10	Stray light & background light					<1.00E-12

Dominant → U1

The final contrast has been estimated within factor of 2.

Summary & Future Works

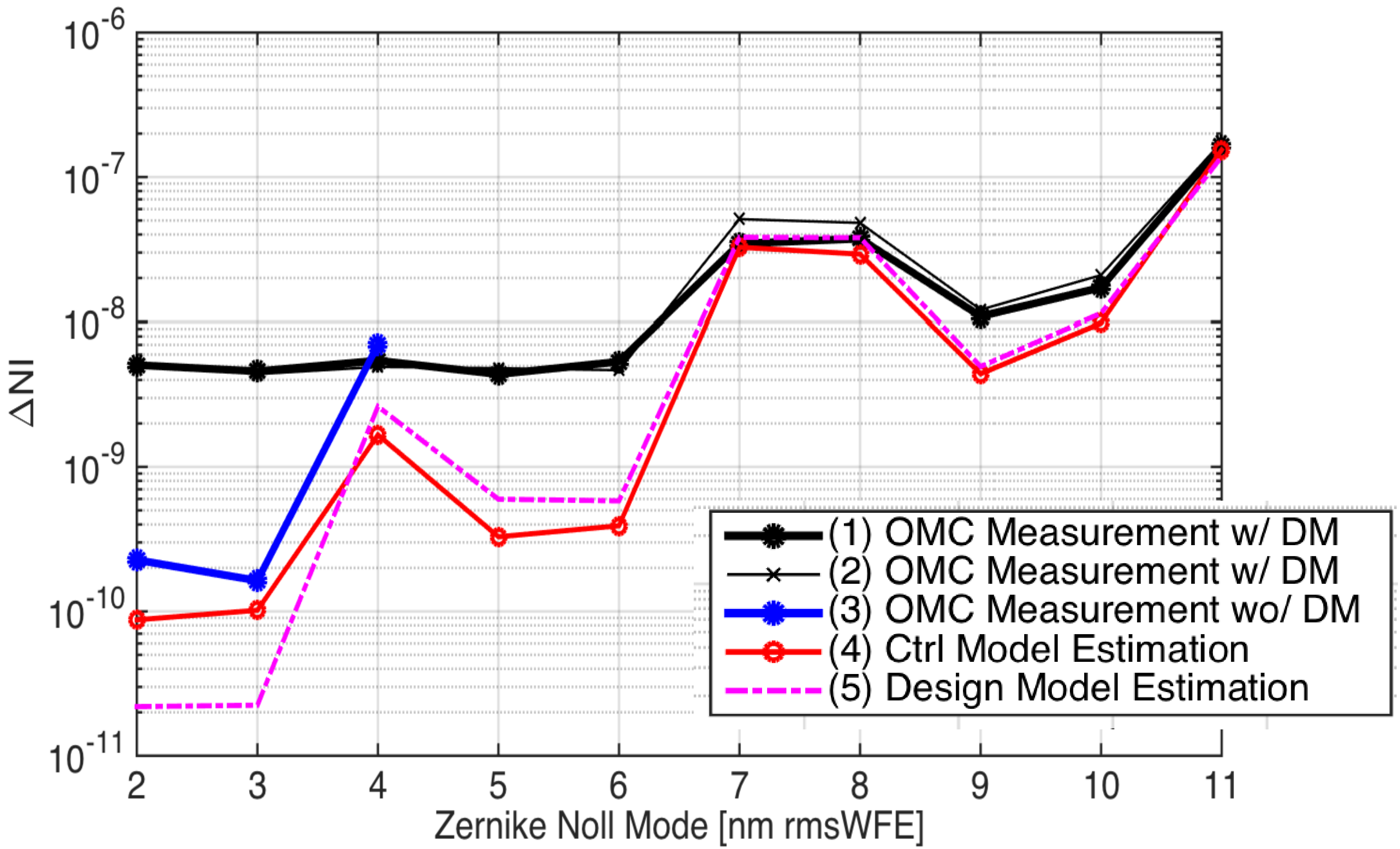
- Summary
  - We have demonstrated generating a high contrast image in the WFIRST-like dynamic environment.
  - The contrast is predictable within factor of 2.
  - The best achieved contrast in the static environment is 1.60E-9 @10% BW, 550 nm, 3-9 λ/D, highest contrast demonstrated ever in the testbed environment with an obscured telescope pupil.
- Next Steps in CY2017
  1. Low photon flux (flight-like) test.
  2. Update the OTA-Simulator to simulate flight-like polarization and increase perturbation DoF.
  3. Off-Axis control to improve the LoS Sensitivity.

Acknowledgement

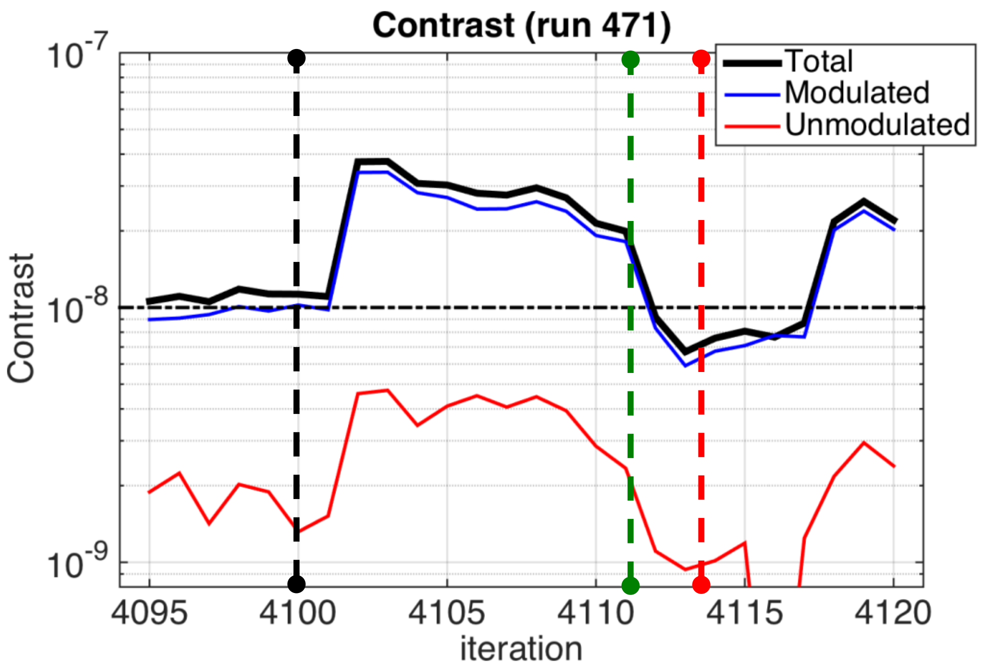
Presented WFIRST coronagraph technology development work was carried out at the Jet Propulsion Laboratory and Princeton University using funding from NASA SMD and STMD

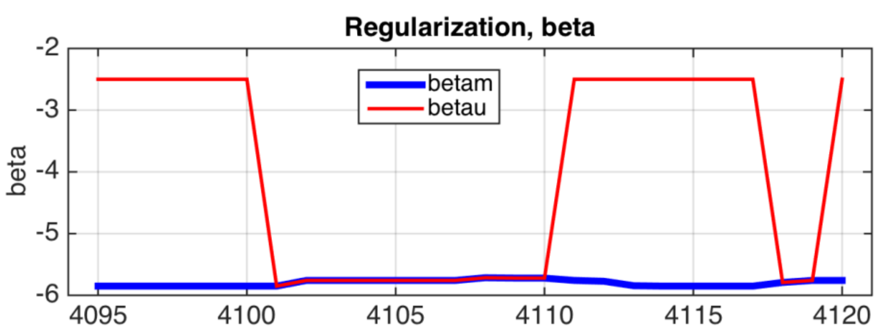
Appendix

Zernike Wavefont Error Sensitivity

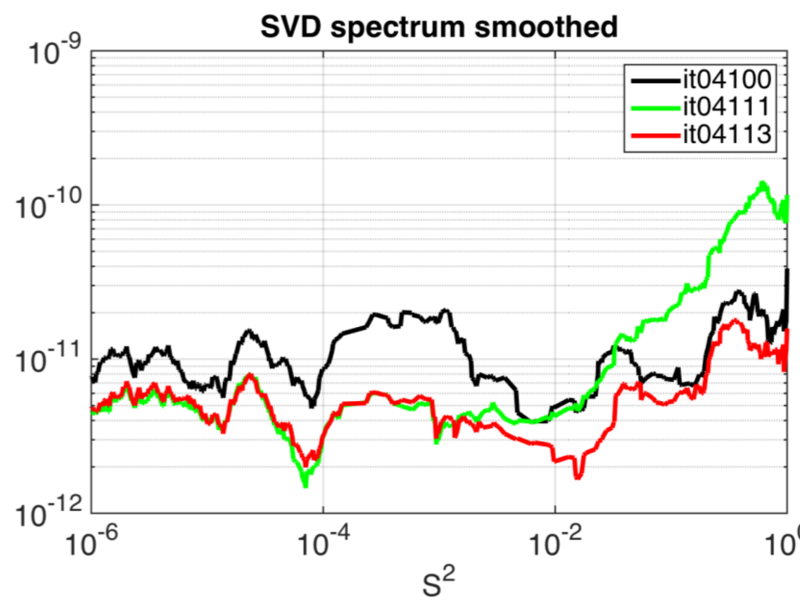


The β scheduling





- ***Distinguished feature in TB***
  - *Hard mode reduction* when β: -2.5 → -6.
  - *Easy mode boost* when β: -2.5 → -6.
  - *Easy mode removal* when β: -6 → -2.5.
  - *Hard mode unchanged* when β: -6 → -2.5.
  - *Low SVD Creep*.
- **Easy mode boost is due to calibration error**
- **High mode reduction is benefit of this strategy.**



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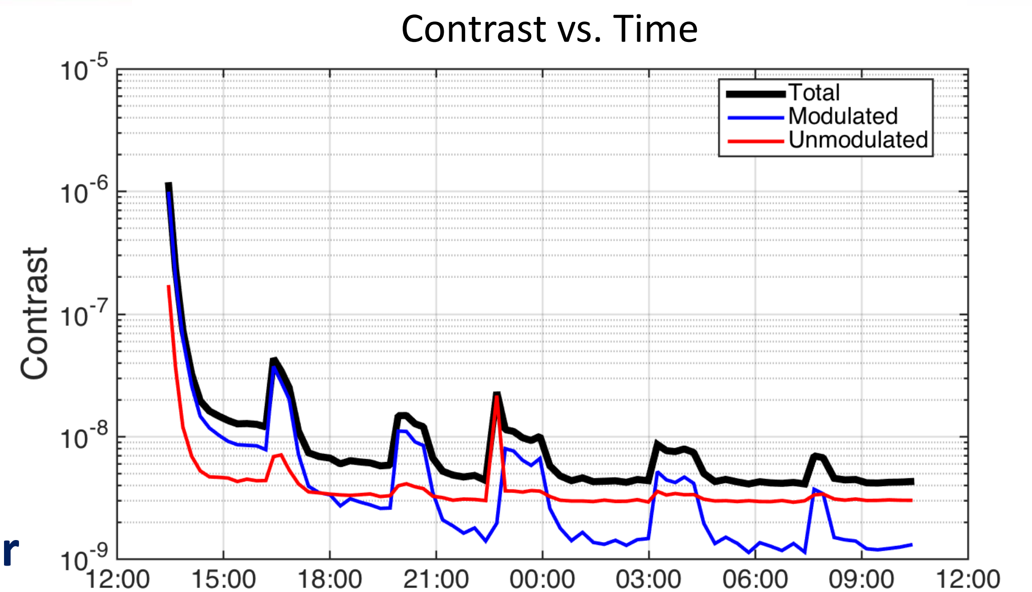
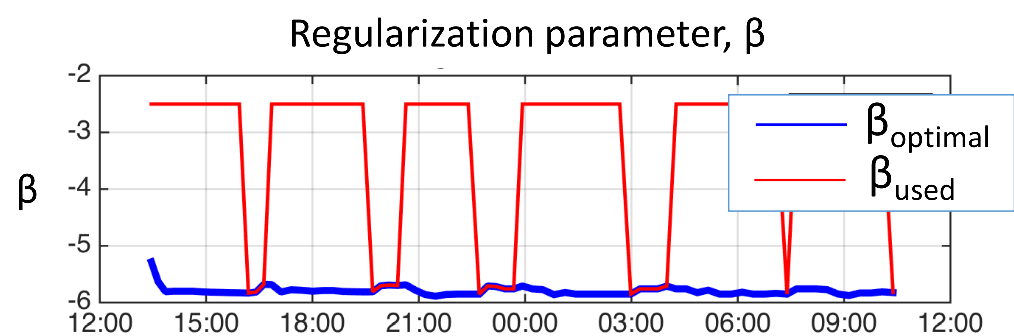
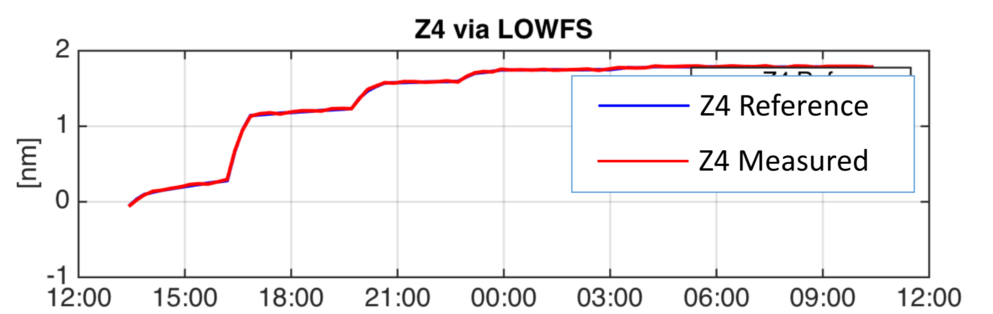
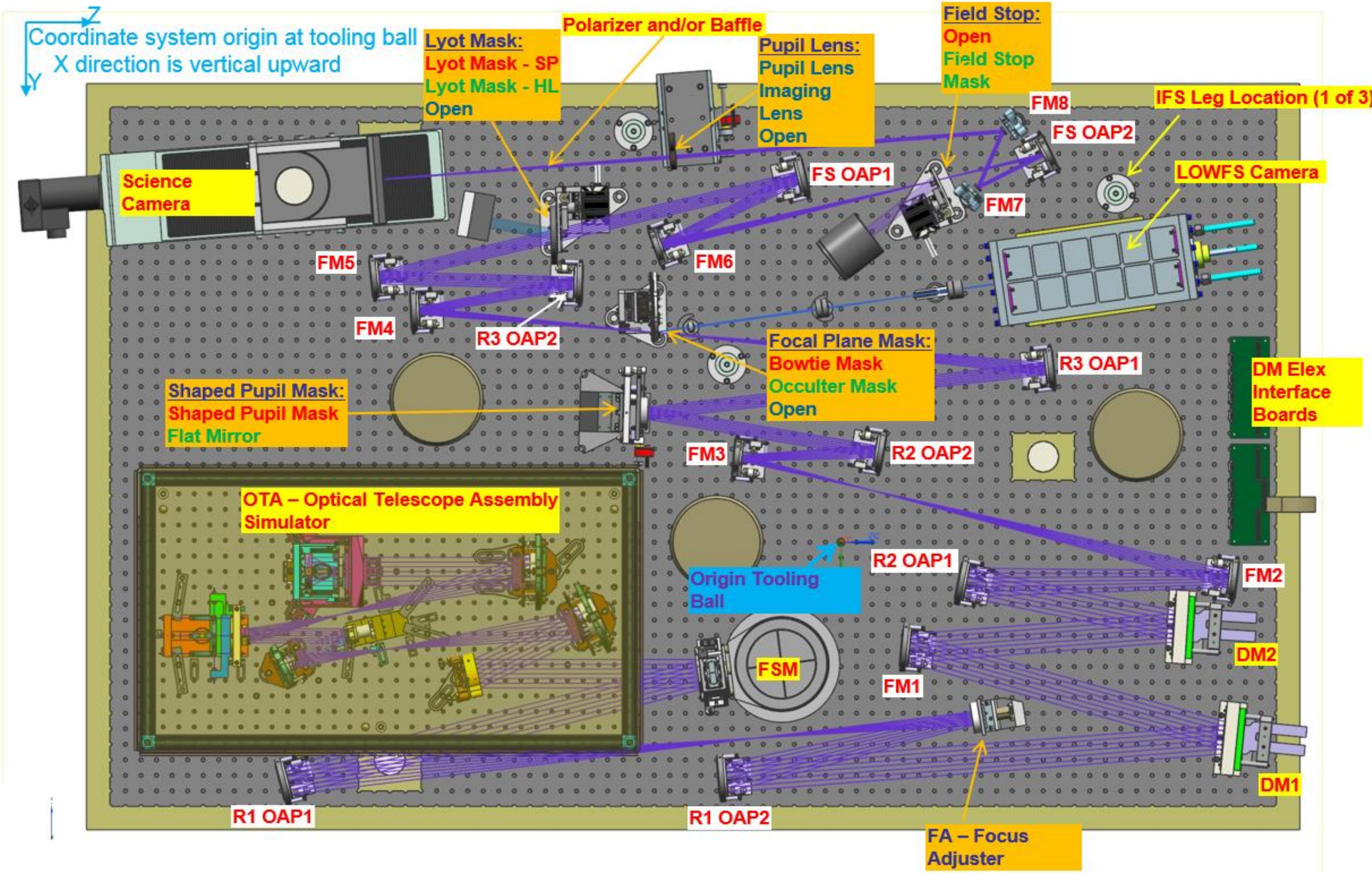






Dynamic OMC Testbed (2/2)



Mechanisms in Orange boxes: red is shaped-pupil mode and green is hybrid Lyot mode

Table is invar 78” x 48”