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WFIRST Coronagraph Technology Development

Milestone #9 Report: Occulting Mask Coronagraph Dynamic Broadband Demonstration

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Milestone 9

Scope, Objectives, and Results

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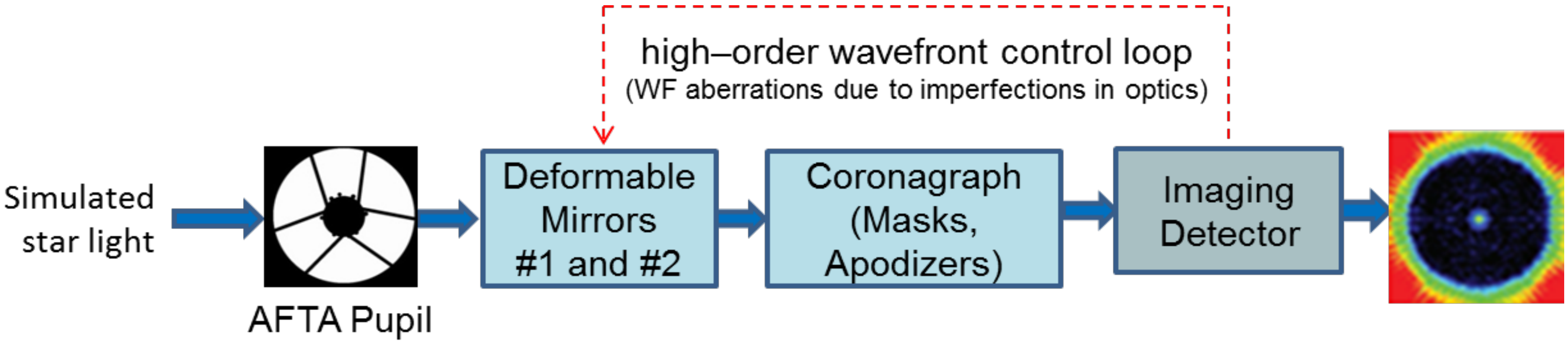
Outline

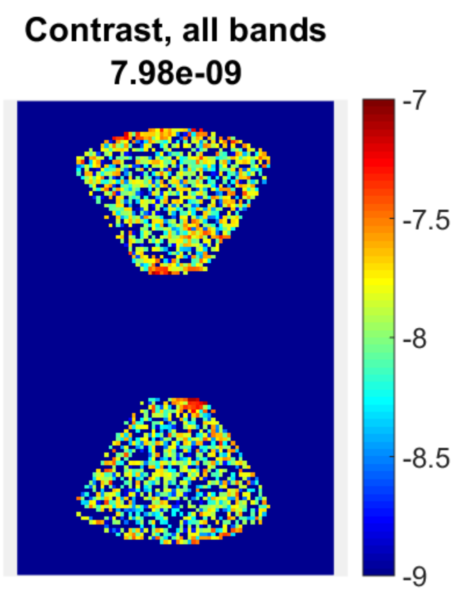
- **Milestone 9 definition and result summary**
- **Dynamic OMC testbed overview**
- **Dynamic testing**
  - WFIRST on-orbit dynamic disturbance and LOWFS architecture
  - Pointing correction tests using FSM
  - Low order correction tests using DM
- **Contrast level in new OMC testbed**
  - Shaped pupil mode
  - Hybrid Lyot mode
  - Instrument contribution vs. GSE contribution
- **Model validation**
- **Simulated planet**
- **Summary**

Milestone 5 Recap (Sept 2015)

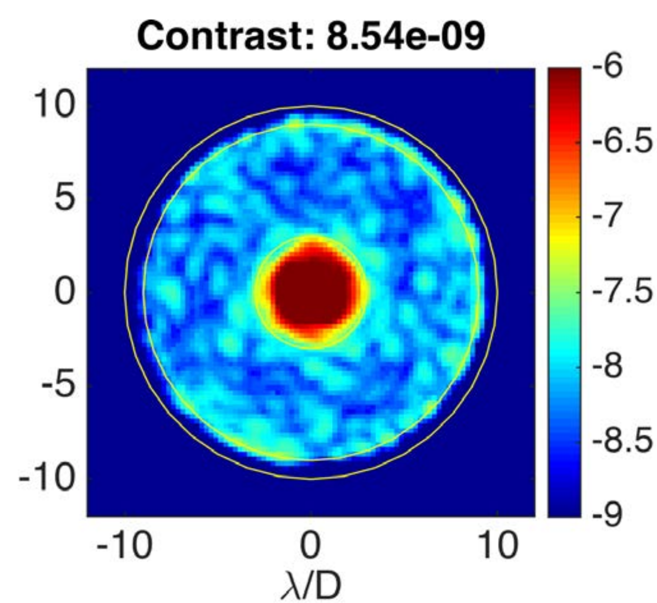
- Both shaped pupil and hybrid Lyot coronagraph designs for WFIRST reached ~8×10^{-9} raw contrast in their respective <u>static</u> testbeds



SPC

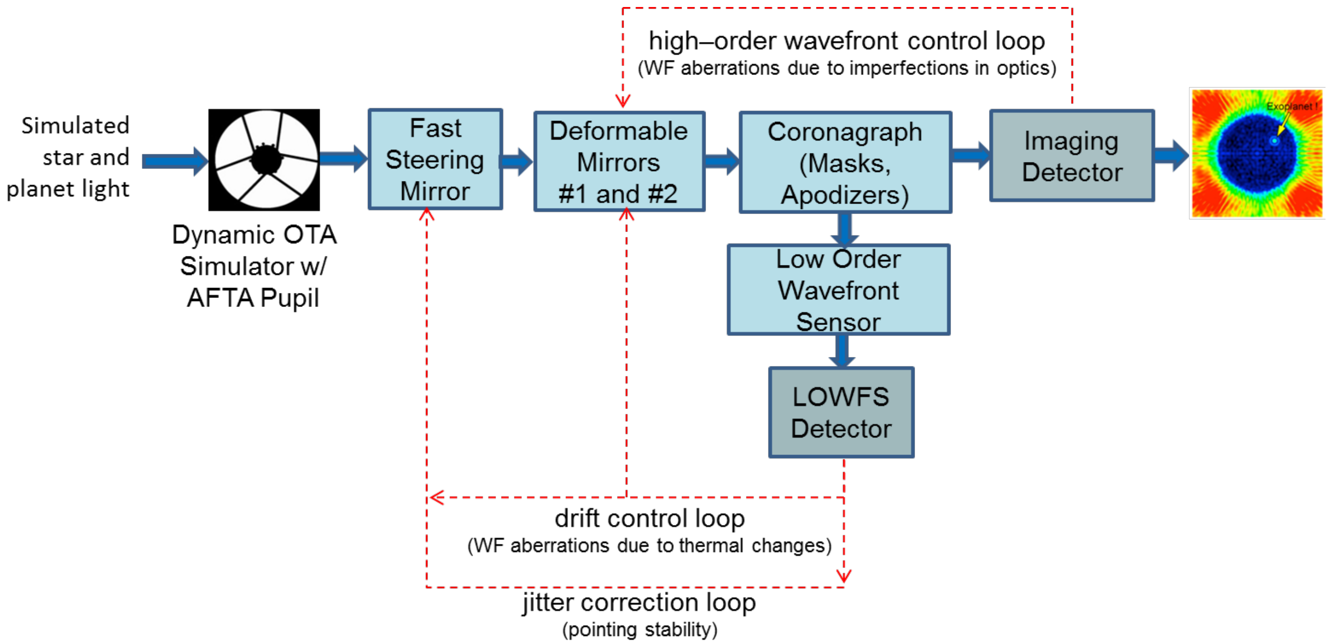


HLC



Milestone 9 Description from 3/23/2014

- ***Milestone 9*: Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.**
- ***Verification Method*: Testbed raw contrast**
  - **Raw contrast and effective throughput must be demonstrated at working angles consistent with coronagraph science requirements**
  - Includes OTA with AFTA pupil producing dynamic wavefront disturbances, LOWFS/C, and planet simulator
  - OMC demonstration means that *at least one* of the two coronagraph technologies comprising OMC demonstrates the required level of performance in a representative dynamic environment



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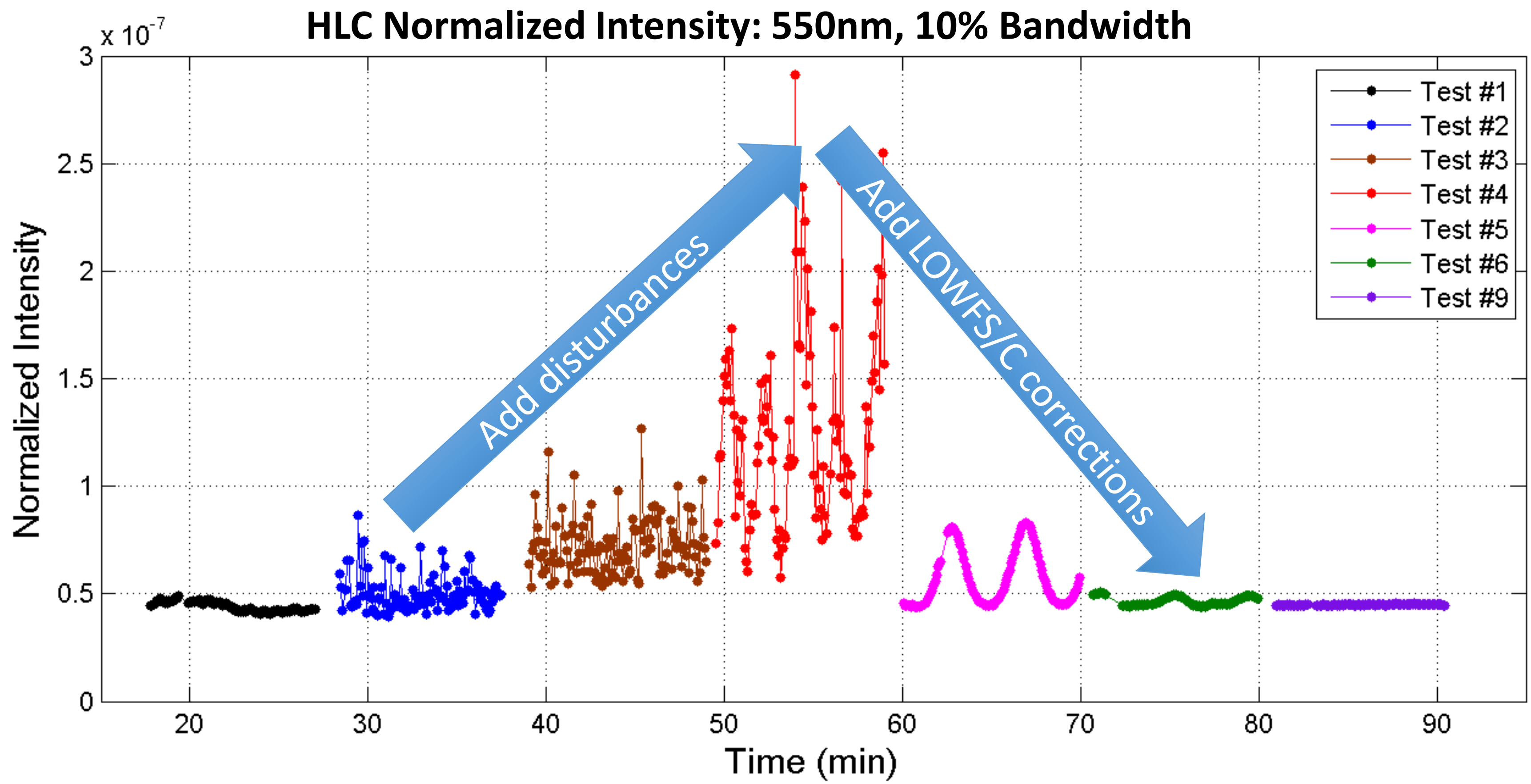
Milestone 9 Objectives and Results

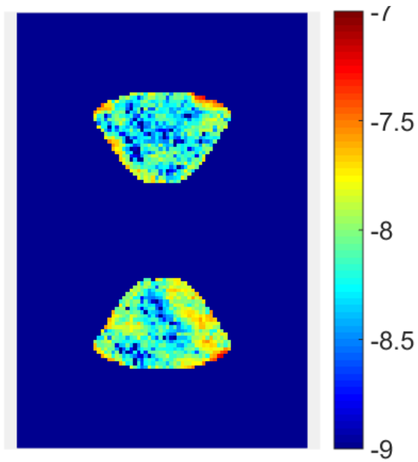
Aspect of Milestone 9	Status	Comments
Coronagraph works with tip/tilt loop closed	Done	Pointing error suppression demonstrated
Coronagraph works with LOWFE loop closed using DM	Done	Low order wavefront control demonstrated with deformable mirror
Broadband 10% dark hole $< 10^{-8}$	Done (new)	Done after front end OGSE was reconfigured. Previously the result was dominated by ~$2x10^{-8}$ unmodulated residual generated by OGSE (pseudo star + telescope simulator)
Measure throughput	Done	Measured geometric and Strehl throughput
Simulate planet	Done	Optically introduced simulated off-axis planet
Model validation and testbed error budgets	Done	Good correlation (MUF < 2) of model prediction and CGI testbed performance (GSE effects aside).

OMC Dynamic Testing

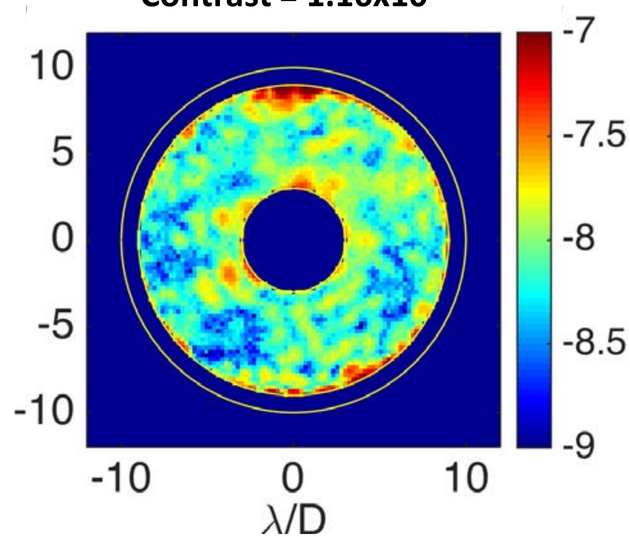


Dynamic Contrast Summary

Contrast = 9.15×10^{-9}



Contrast = 1.16×10^{-8}



	Demonstrated in OMC Testbed	Extrapolated to WFIRST Flight Conditions
Static Raw Contrast	9.15×10^{-9} (SPC) 1.16×10^{-8} (HLC)*	9.15×10^{-9} (SPC) 1.16×10^{-8} (HLC)*
Contrast Increase due to Residual Pointing Drift and Jitter	$< 0.4 \times 10^{-9}$ (HLC)	$< 0.4 \times 10^{-9}$ (HLC)
Contrast Increase due to Residual Focus Drift	5×10^{-9} (HLC)	0.31×10^{-9} (HLC)**

* HLC nulling run in progress after a recent H/W change; reached 1.0×10^{-8} 3-8.8 λ/D

** conservative extrapolation used

Dynamic OMC testbed

Overview of the milestone testbed

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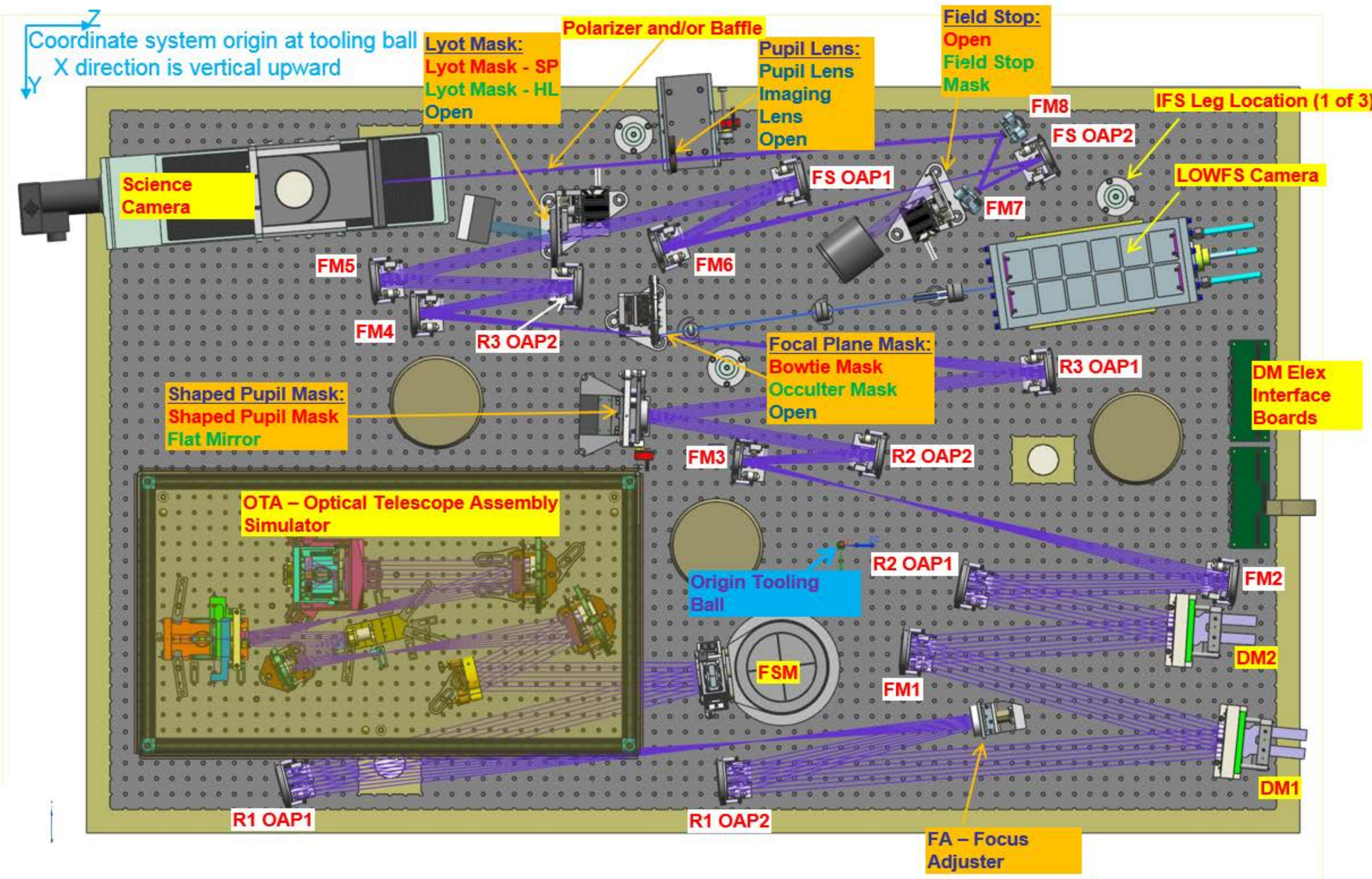
OMC Dynamic Testbed [1 of 3]

- **Completed and commissioned advanced testbed that introduces many new features for high fidelity testing of space coronagraphs:**
  - New masks and stops for two coronagraph modes (Shaped Pupil and Hybrid Lyot) on the same testbed – similar to WFIRST flight coronagraph instrument – with mechanisms to remotely switch between these two modes
  - Mini-WFIRST telescope simulator with a representative obscured pupil that can produce on-orbit dynamic disturbances such as observatory pointing drift and jitter and thermal drifts
  - Low-order wavefront sensor that uses the rejected "star" light and is capable of both sensing sub-angstrom level wavefront errors and controlling a fast-steering mirror, focus adjustment, and a deformable mirror to reduce these disturbances
  - Stable, extensively modeled optical mounts to enable the validation of coronagraph structural, thermal, optical, performance (STOP) models.
  - Improvements made to the vacuum tank's mechanical isolation, thermal insulation, and stray light control

OMC Dynamic Testbed [2 of 3]



Mechanisms in Orange boxes: red is shaped-pupil mode and green is hybrid Lyot mode
Table is invar 78" x 48"

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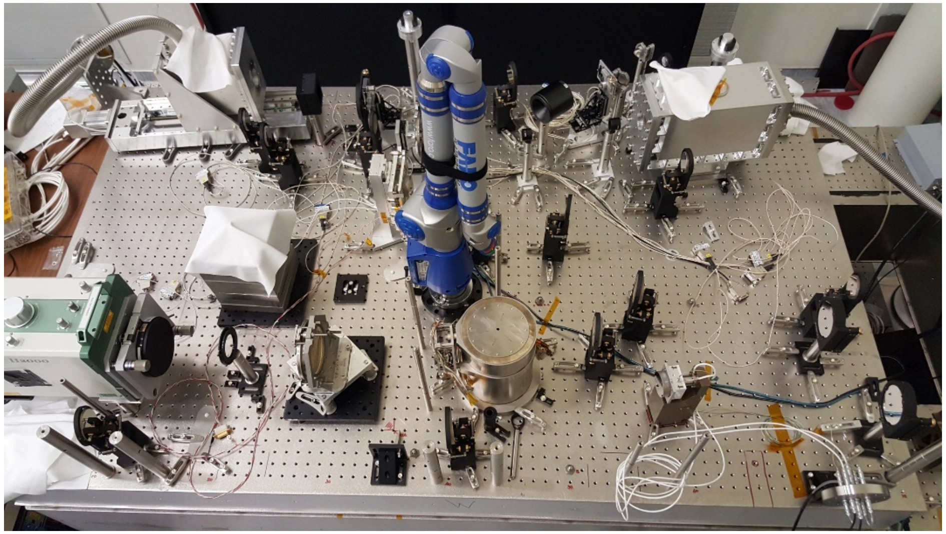
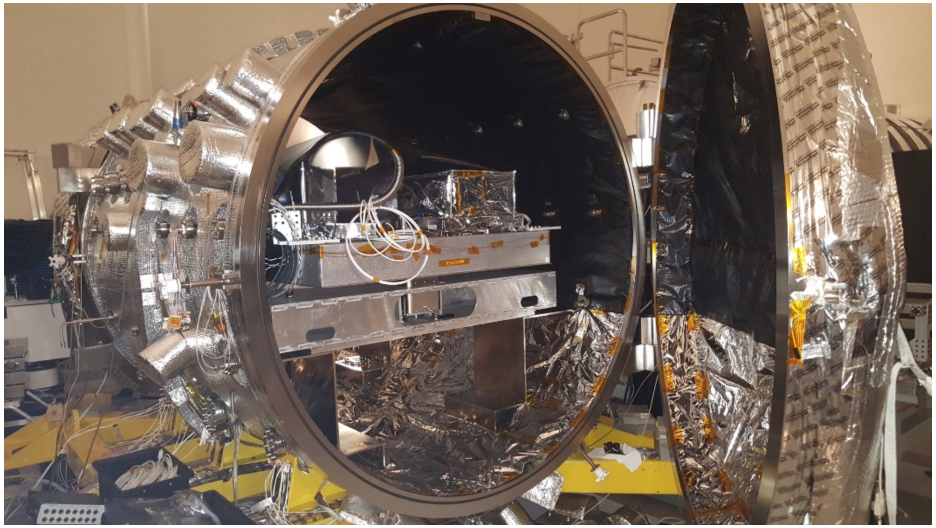
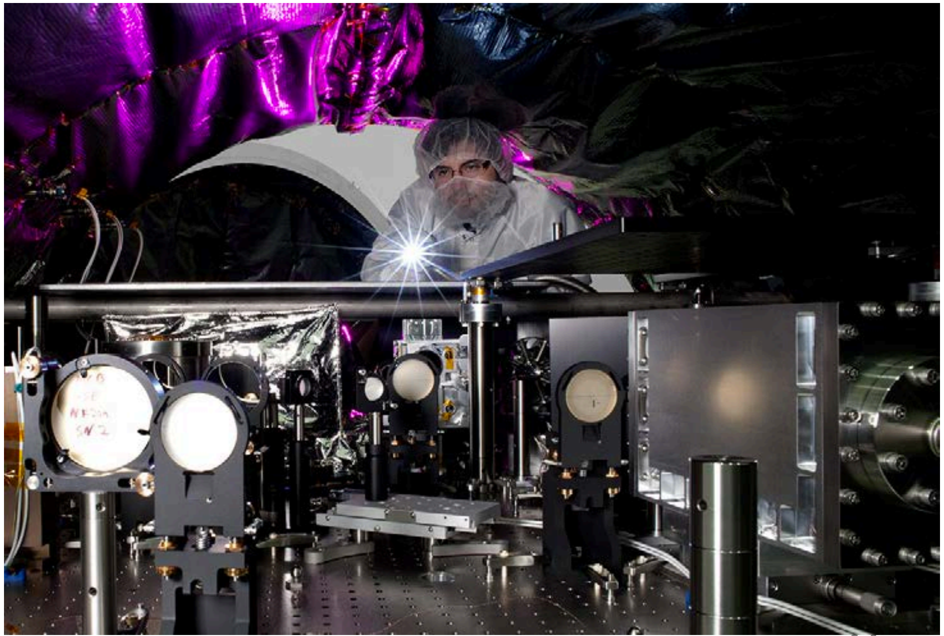
OMC Dynamic Testbed [3 of 3]







Dynamic Testing

Low Order Wavefront Sensor (LOWFS) demonstration

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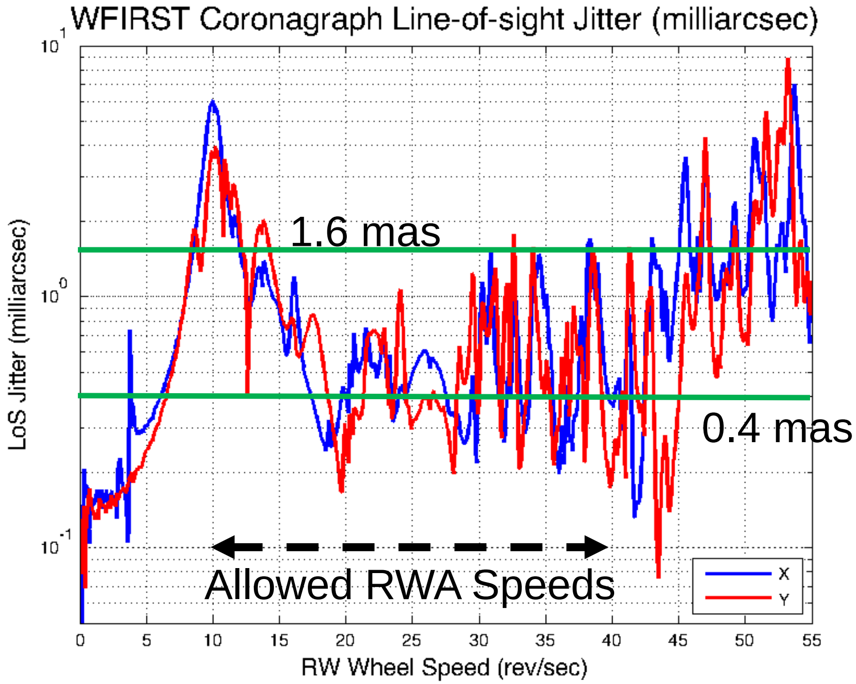
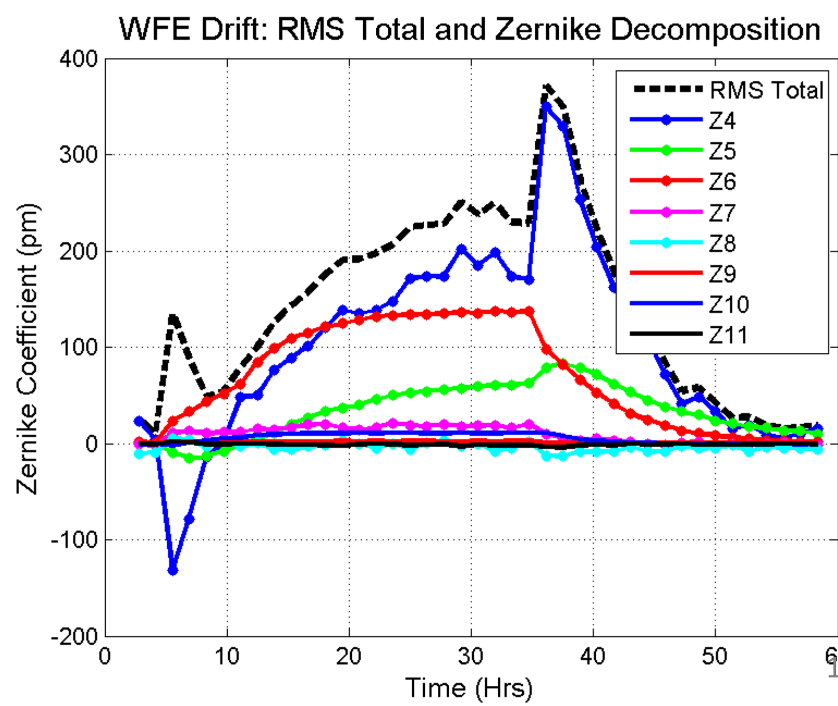
WFIRST Telescope LoS Jitter and WFE Drift

- **Line-of-sight drift and jitter (Cycle 5)**
  - Drift (<2Hz): ~14 milli-arcsec ACS pointing.
  - Jitter (>2Hz): < 10 milli-arcsec. Peaks ~10 Hz, multiple harmonics at each RWA speed.
  - WFIRST observatory requirements allow 14 mas drift and 14 mas jitter (rms per axis)
- **WFE drift (Cycle 5)**
  - Mostly thermally induced rigid body motion of the telescope optics.
  - Slow varying, typically <10 pm/hour.
  - Dominant WFE are: focus (Z4), astigmatism (Z5, Z6) and coma (Z7, Z8).

LoS vs RWA Speed



WFE Drift



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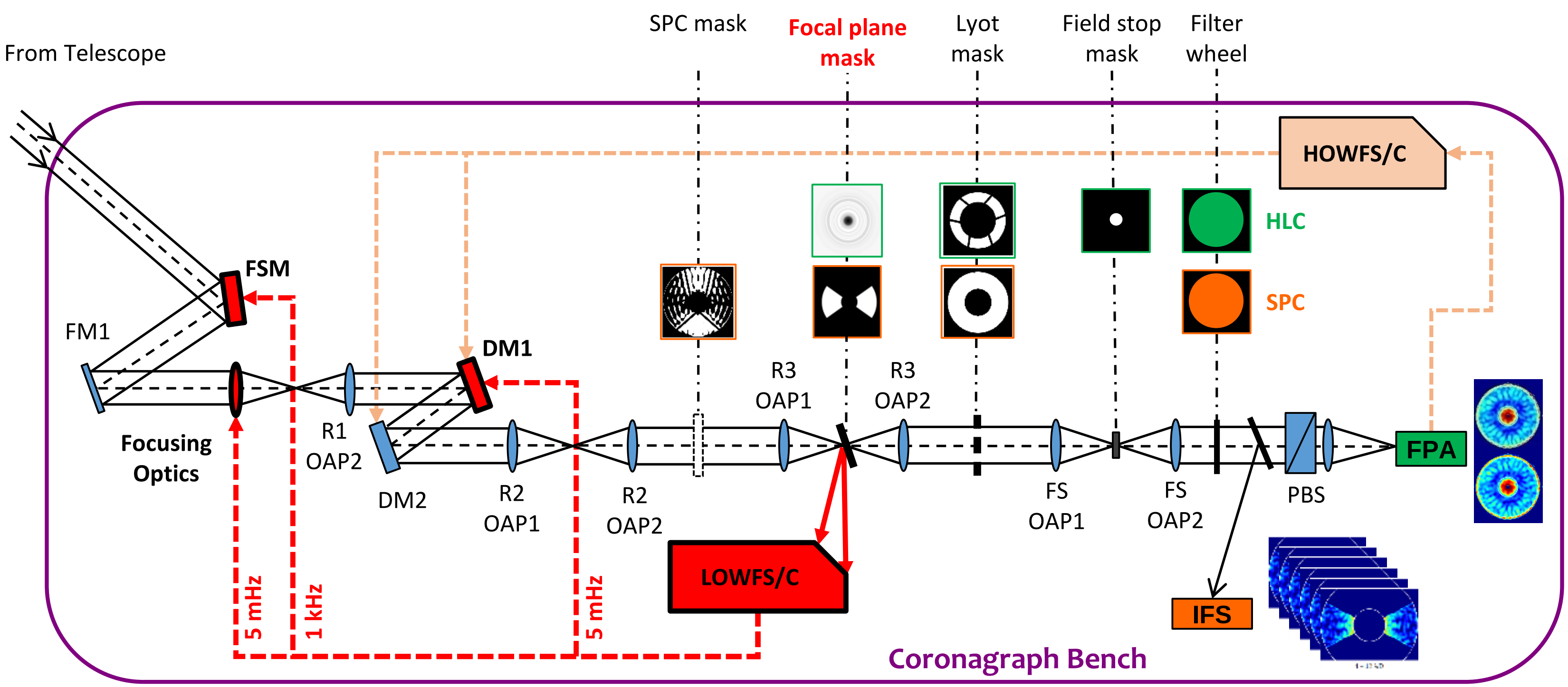
LOWFS/C Overview



- LOWFS/C subsystem measures and controls line-of-sight (LoS) jitter and drift as well as the thermally induced low order wavefront drift
- Differential sensor referenced to coronagraph wavefront control: maintains wavefront established for high contrast (HOWFS/C)
- Uses rejected starlight from occulter which reduces non-common path error
- LOWFS/C telemetry can be used for coronagraph data post-processing

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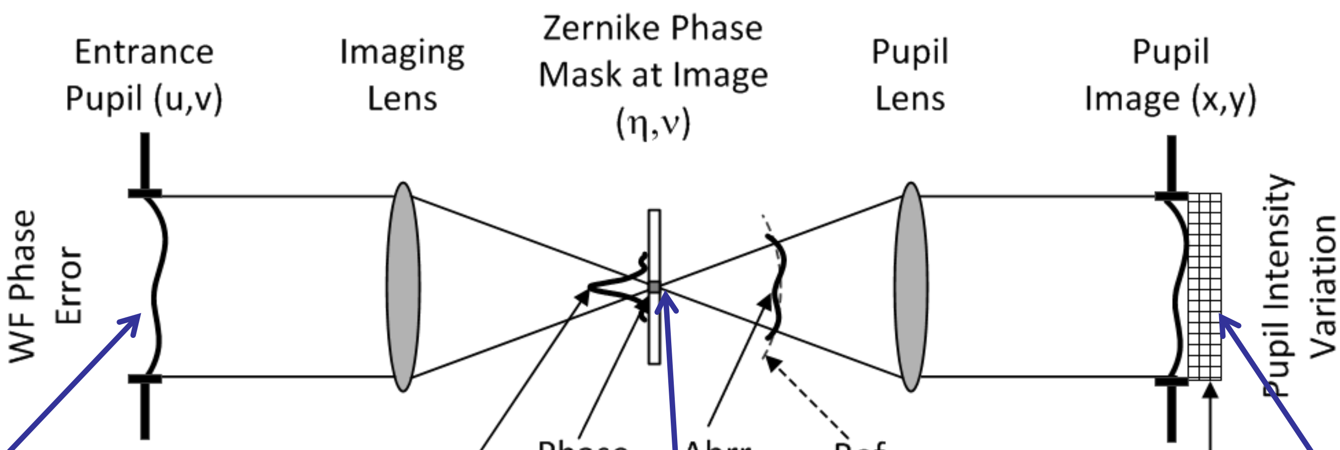
Zernike Wavefront Sensor Concept

- **Zernike WFS (ZWFS) measures wavefront error (WFE) from interference between the aberrated WF and the reference WF generated by a phase dimple (diameter ~ λ/D)**
  - At phase shift of $\pi/2$, pupil image brightness variation is proportional to the WFE: $\Delta I \sim \pm 2\varphi$
  - Same principle as Zernike phase contrast microscope
- **ZWFS uses linearized differential image to sense the delta WFE**
  - ZWFS sensed pupil is imaged to CCD at 16x16 pixels for sensing WFE up to spherical aberration Z11
  - 128 nm spectral band (throughput vs. accuracy trade-off)
- **ZWFS converts pupil phase variation into intensity variation on the LOWFS camera**



$$E(u,v) = P(u,v)\cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$

At $\theta = \pi/2$

$$I = A^2\left(1 + 2\varphi(x,y) + \varepsilon(x,y)^2 + \varphi^2\right)$$

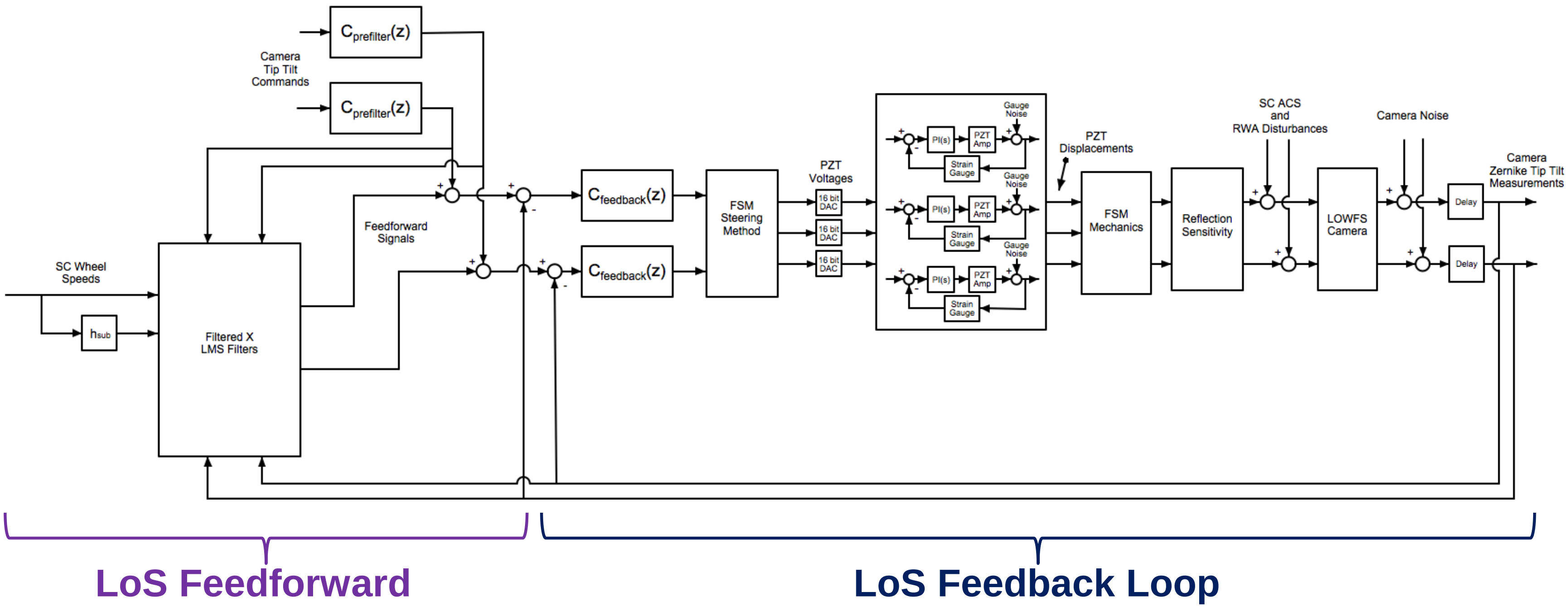
$$\hat{E}(\eta,\upsilon) = A\cdot CPSF(\eta,\upsilon)e^{i\theta} + A\cdot CPSF(\eta,\upsilon)\otimes F\{\varepsilon(u,v) + i\varphi(u,v)\}$$

$$Z = \alpha^{-1}(K^T K)^{-1} K^T \bullet \Delta I$$

ZWFS sensing algorithm

LOWFS/C Line-of-Sight Control Approach

- **Feedback path to cancel slow ACS LoS drift**
  - LOS loop is shaped for **optimal rejection of the ACS disturbance and LOWFS/C sensor noise.** This is done by balancing the error contribution from sources of jitter, camera noise, and LoS drift from ACS
- **Feedforward path to cancel high frequency tonal LoS jitter from RWAs**
  - RWA speeds used to determine the disturbance frequencies
  - A least-mean-square (LMS) filter estimates the gain and phase of the disturbance
  - Correction commands are directly sent to FSM



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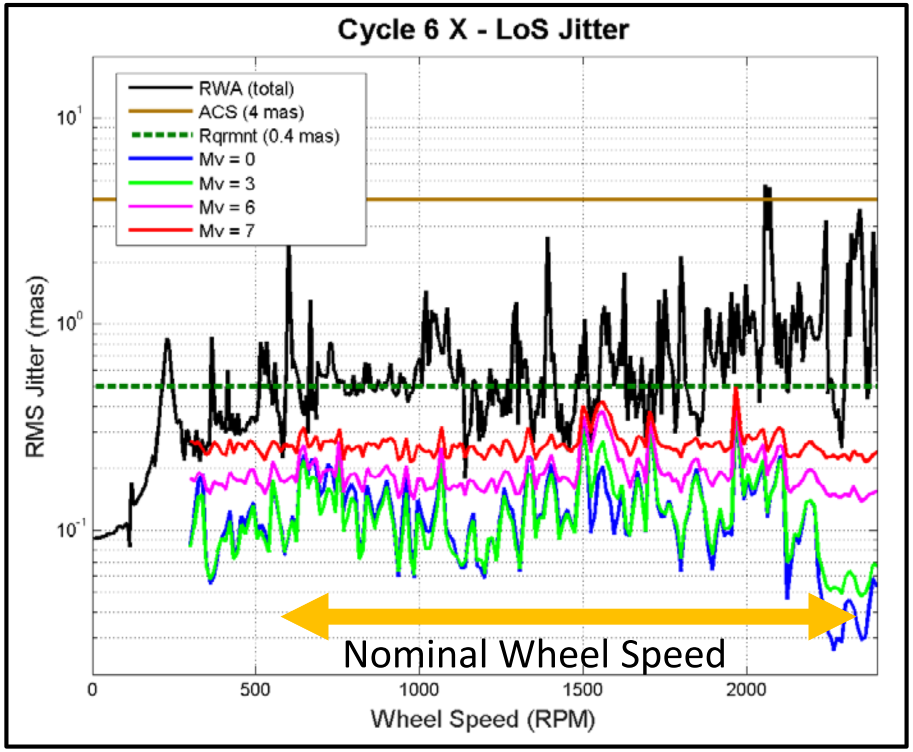
Modeling LoS Correction w/Cycle 6 Input

- **Performance analysis for the latest Cycle 6 ACS + RWA**
  - Cycle 6 jitter profile (8/16/2016, w/ TCA mount mod)
  - RWA nominal operation speed between 600 – 2400 rpm, ramping up over 18 hours
  - Summarized for three residual jitter levels, from the optimal (0.4 mas) to threshold (1.6 mas)
  - Single (highest impact) wheel only
- **LoS error suppression loop performs well for both Cycle 5 and Cycle 6 disturbance**

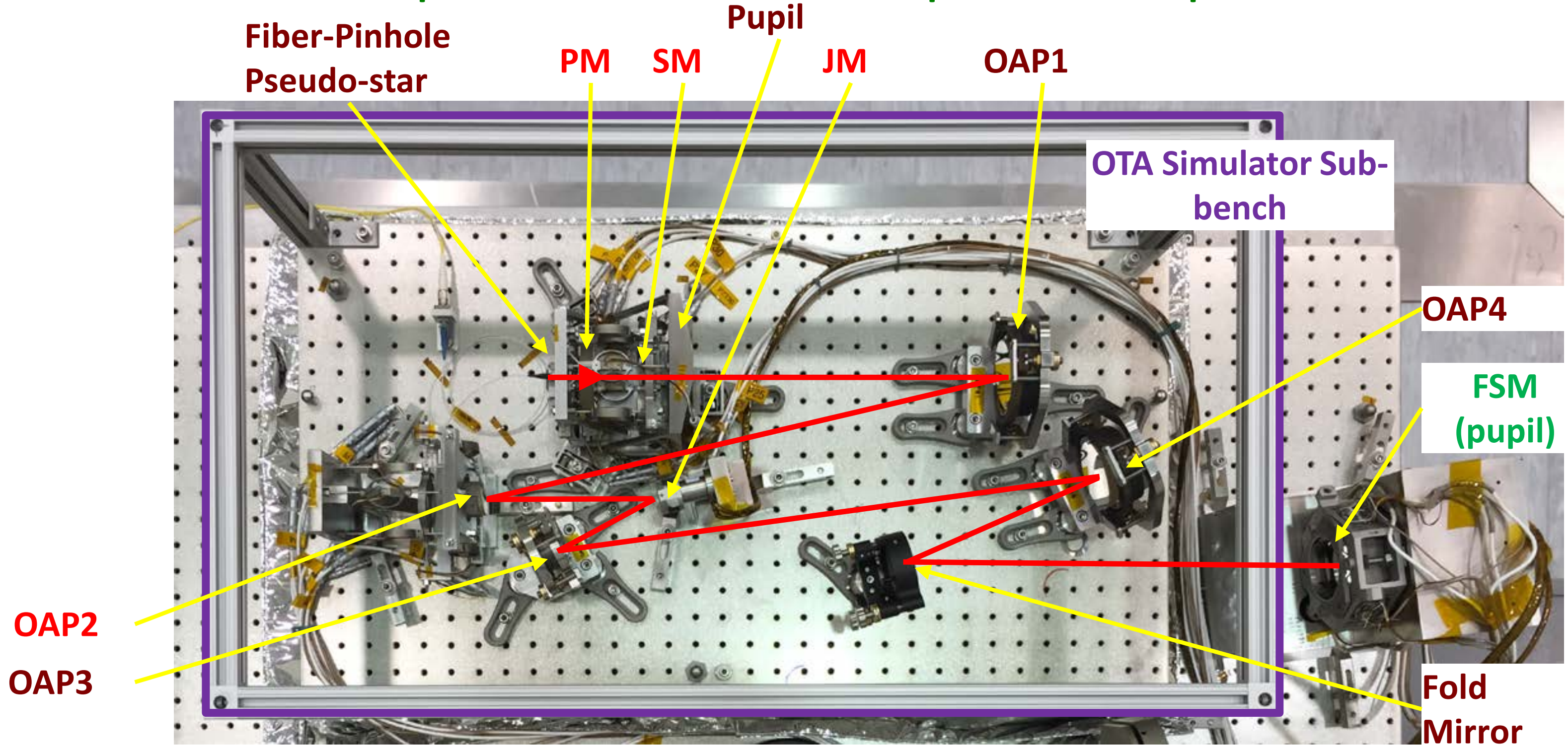
X jitter residual over 10 - 40 rev/sec (600 - 2400 rmp)			
Star Mv	< 0.4	< 0.8	< 1.6
0	99.30%	100%	100%
3	99.30%	100%	100%
6	99.30%	100%	100%
7	97.40%	100%	100%

Y jitter residual over 10 - 40 rev/sec (600 - 2400 rmp)			
Star Mv	< 0.4	< 0.8	< 1.6
0	97.40%	100%	100%
3	98.70%	100%	100%
6	98.00%	100%	100%
7	91.40%	100%	100%



OTA Simulator for OMC Testbed

- **OTA Simulator (OTA-S) is used to inject line-of-sight (tip/tilt) and low order aberration drifts into the coronagraph for the dynamic test**
  - Jitter Mirror is used to inject LoS drift and jitter
  - PZT actuators on the OTA-S telescope and OAP2 are used to inject the low order aberrations (focus, astigmatism, coma)
  - OTA-S LoS and low order WFE modes have been calibrated by Zygo interferometer
- **FSM and DM #1 are used to correct LoS and low order WF error, respectively**
- **More discussion of the pseudo-star and mini-telescope later in this presentation**



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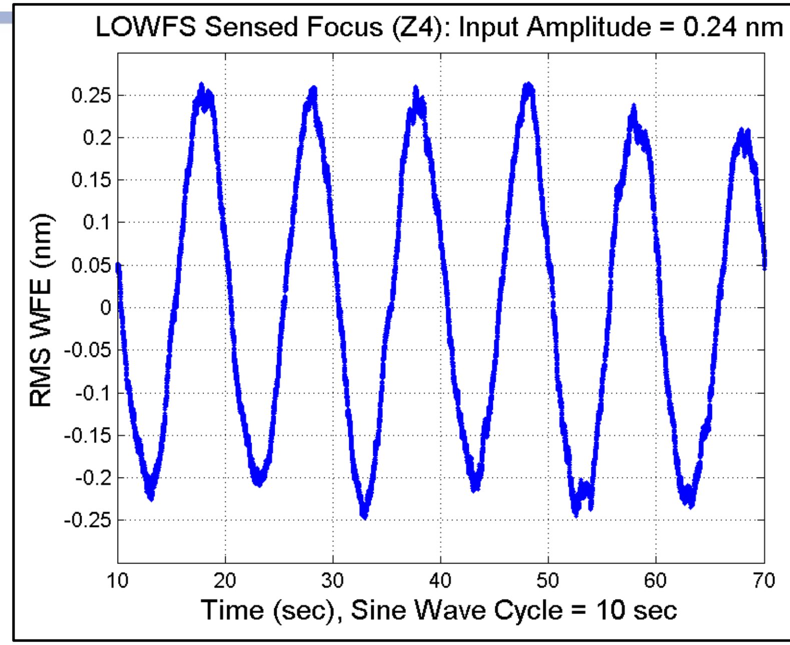
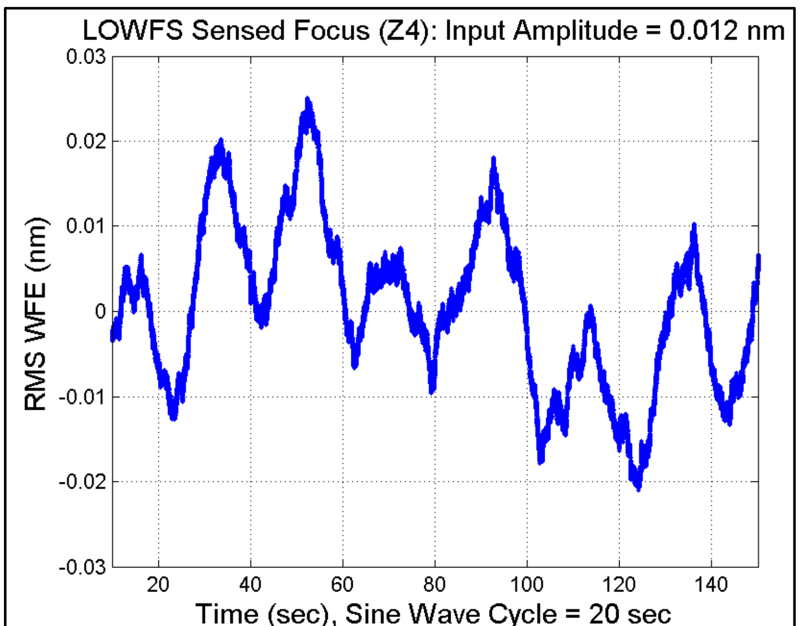
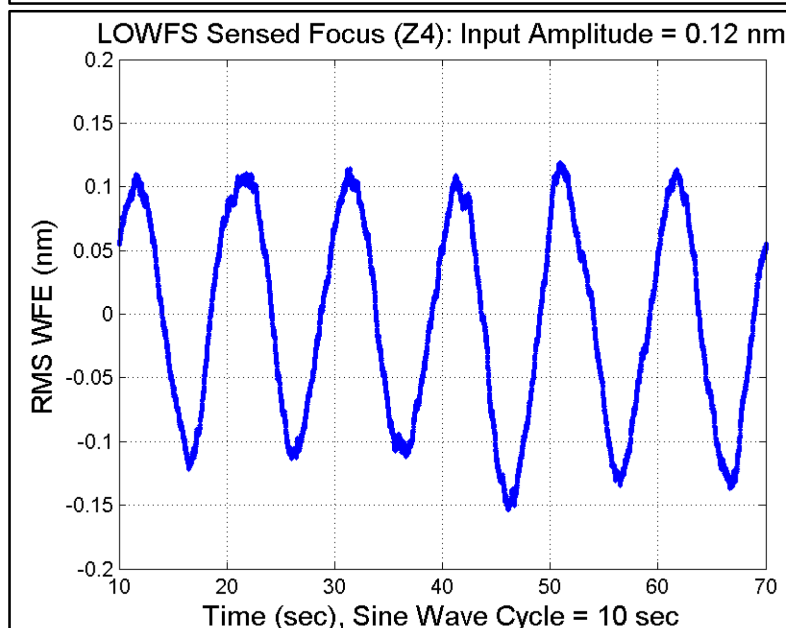
LOWFS Sensitivity: Focus

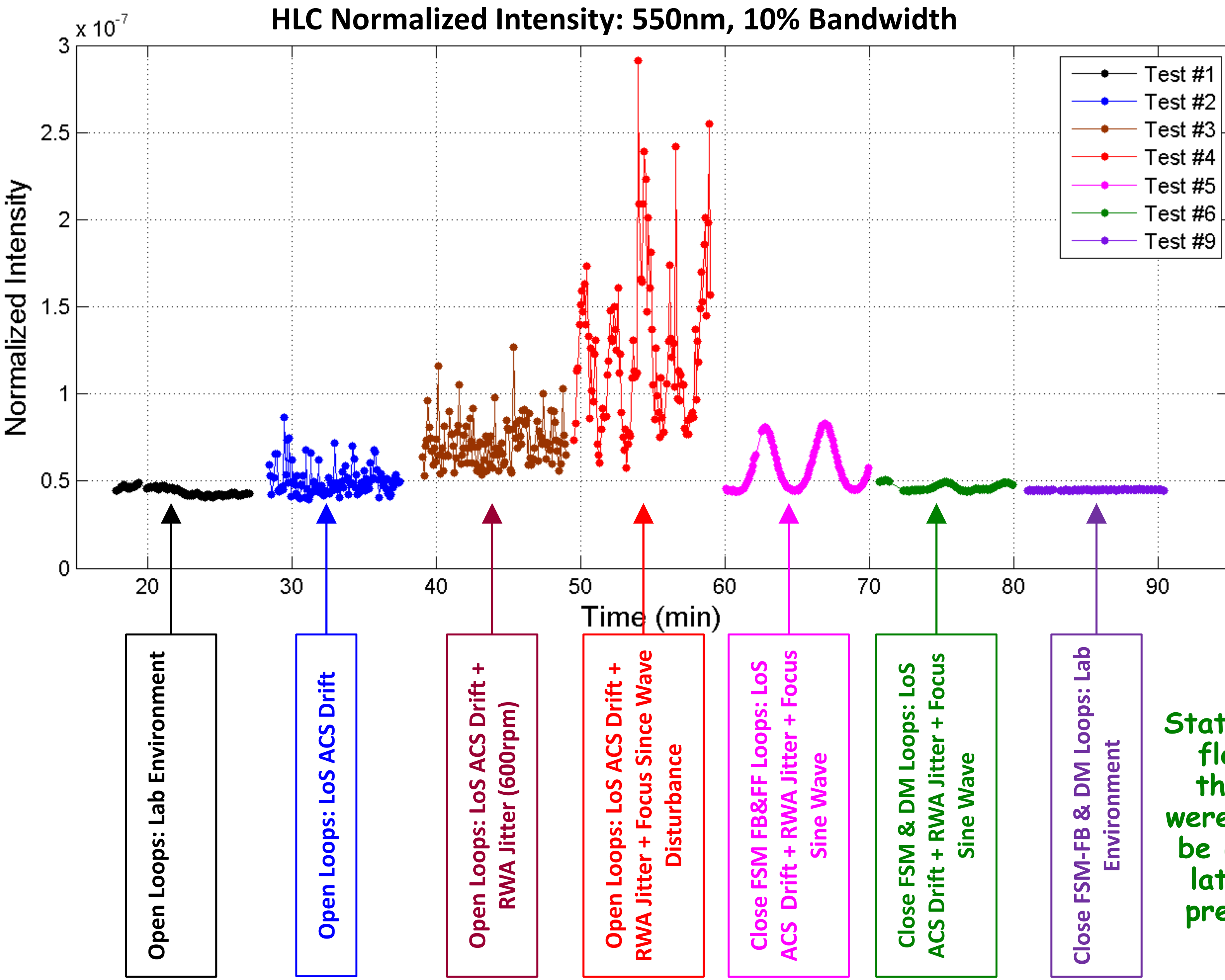
- **Reduced amplitude of OTA-S focus disturbance to create a small focus modulation for LOWFS sensor**
  - Increase modulation cycle period for more frame averaging to reduce sensor noise
  - Signals averaged to reduce noise and detrended to remove testbed focus drift
  - Average: 1, 2, 10 seconds for the plots
- **LOWFS can see focus as small as 12 pm (rms)!**





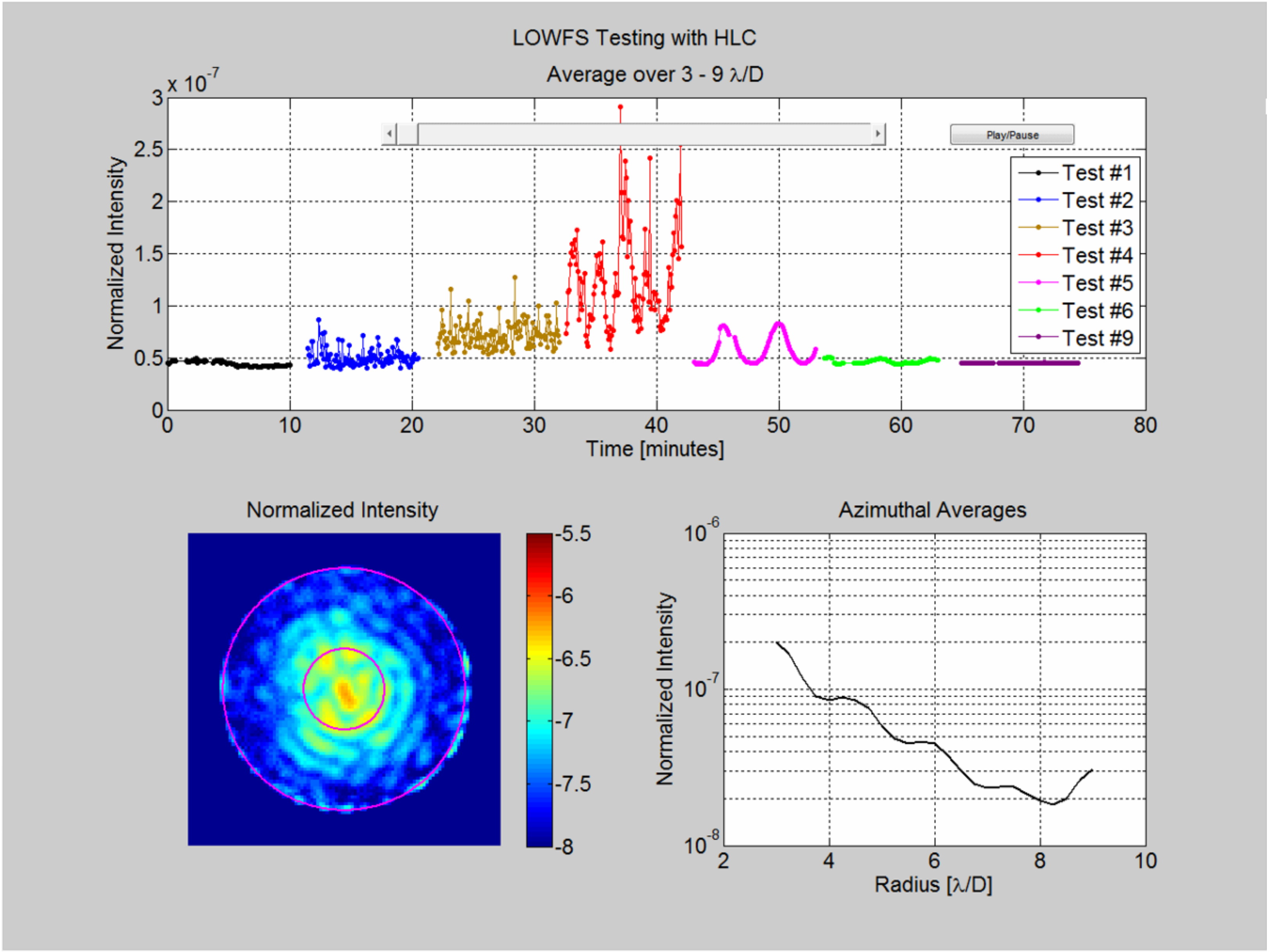


HLC LOWFS/C Dynamic Test



Static contrast floor when these data were taken will be addressed later in the presentation

HLC LOWFS/C Dynamic Test: Movie



HLC LOWFS LoS Correction: Data vs. Model

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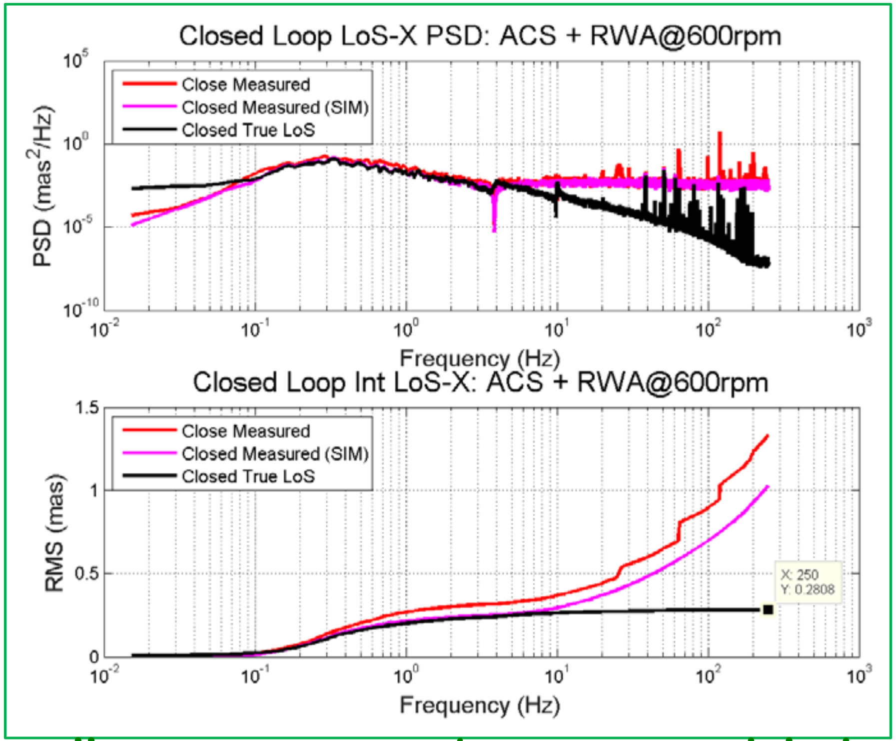
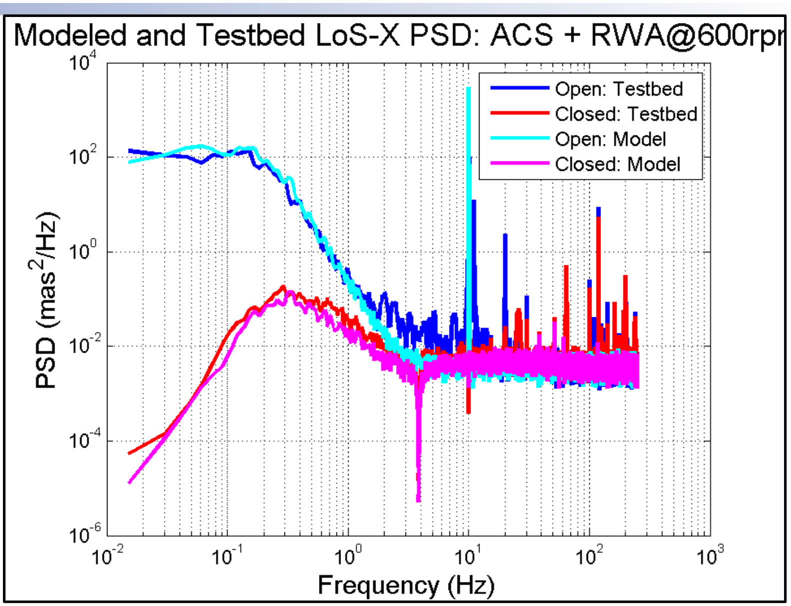
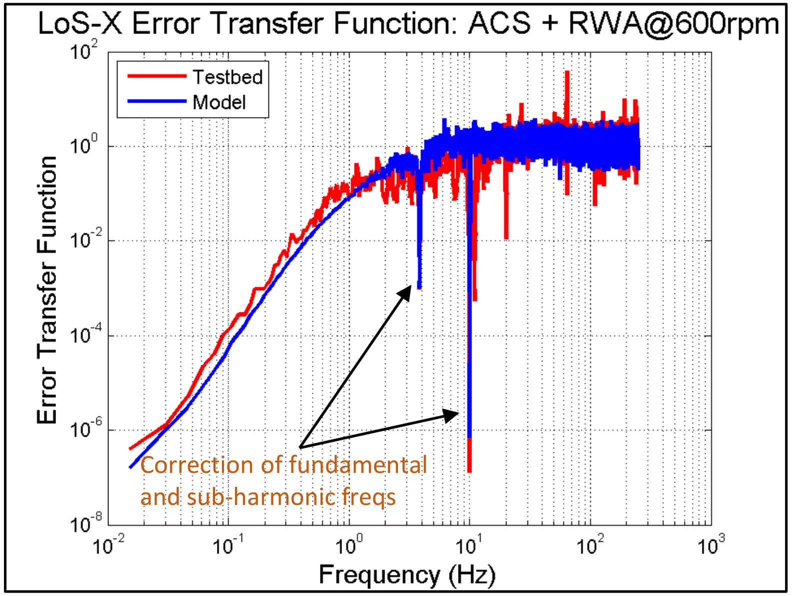
- **Modeled and testbed PSD of open/closed loop in LoS X (upper right plot)**
  - Cycle 5 ACS drift and jitter at wheel speed of 600 rpm
  - Testbed data include lab environment LoS noise
  - Modeled data include sensor noise
- **Modeled and testbed LoS error transfer function calculated from the open and closed loop PSD (lower right plot)**
- **Model predicted true residual LoS-X error without broadband sensor noise (black line below)**
  - FSM loop is not closed on high frequency sensor noise, thus it does not impact loop performance



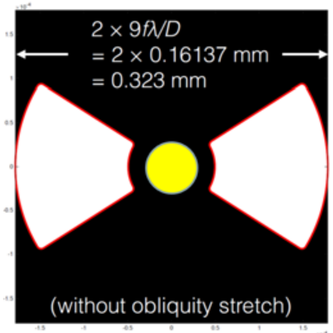


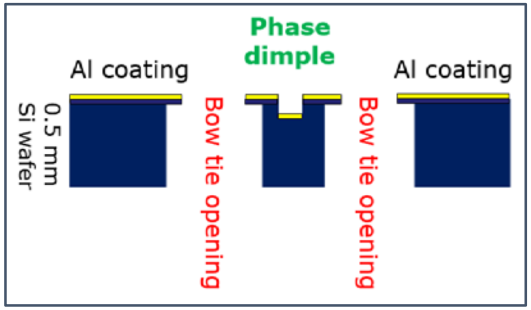


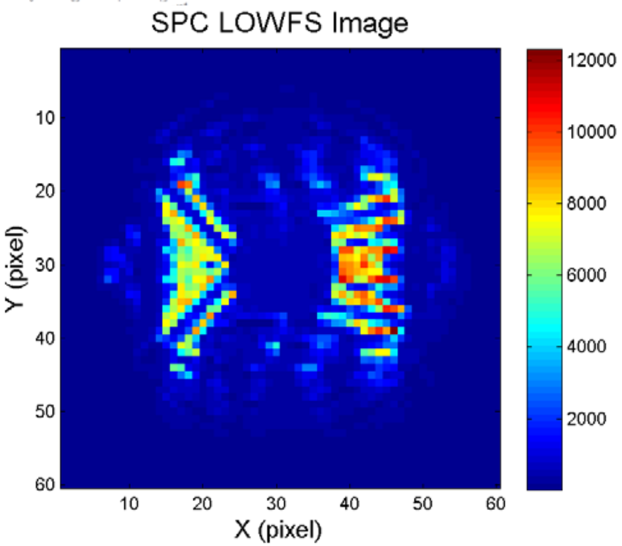
Excellent agreement between modeled and measured LoS loop performance

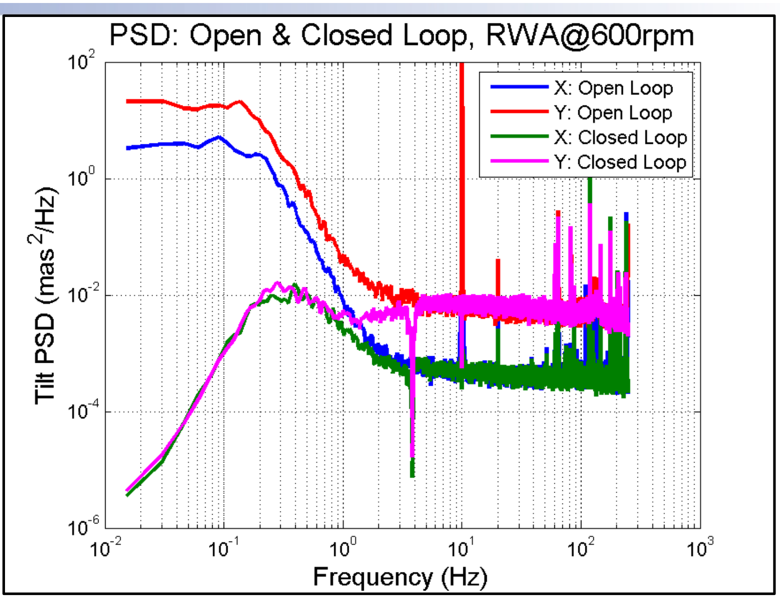
SPC LOWFS LoS Correction

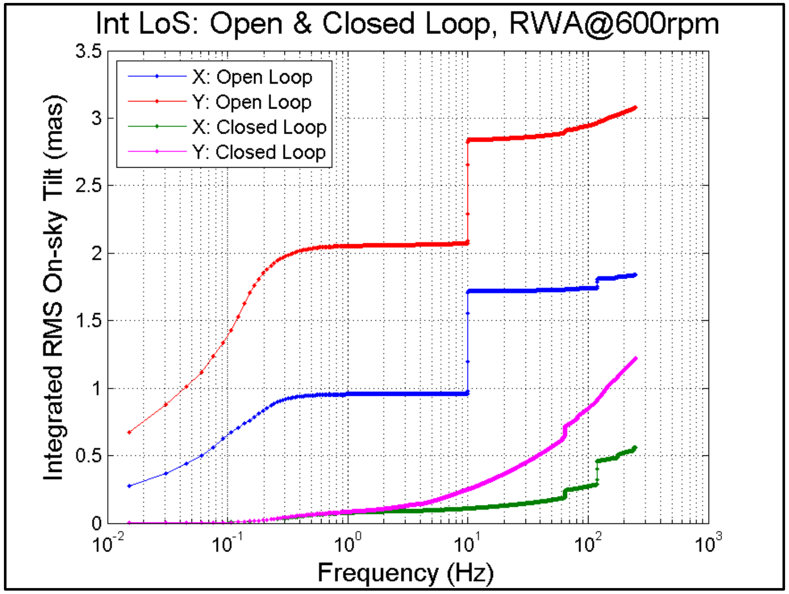
- **Zernike phase dimple built into new SPC "bowtie" occulting masks, fabricated at JPL's MDL**
- **Cycle 5 CBE LoS disturbances tested on the OMC testbed**
- **Residual error is dominated by the LOWFS sensor noise and testbed environment noise**
  - Asymmetric SPC PSF causes more sensor noise in Y







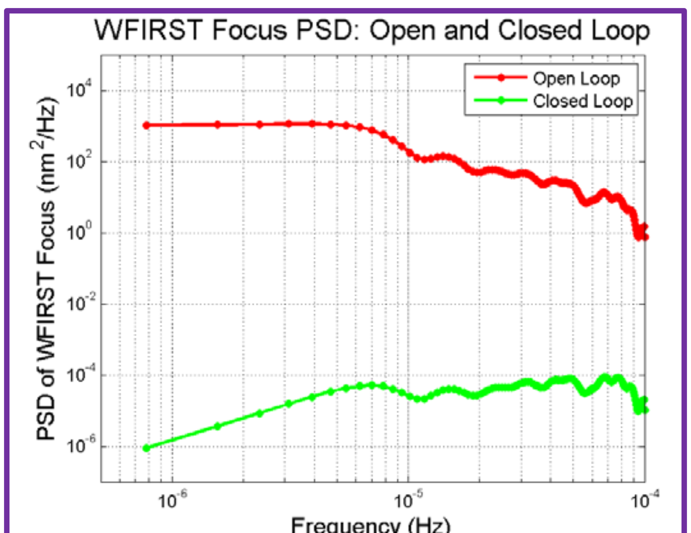


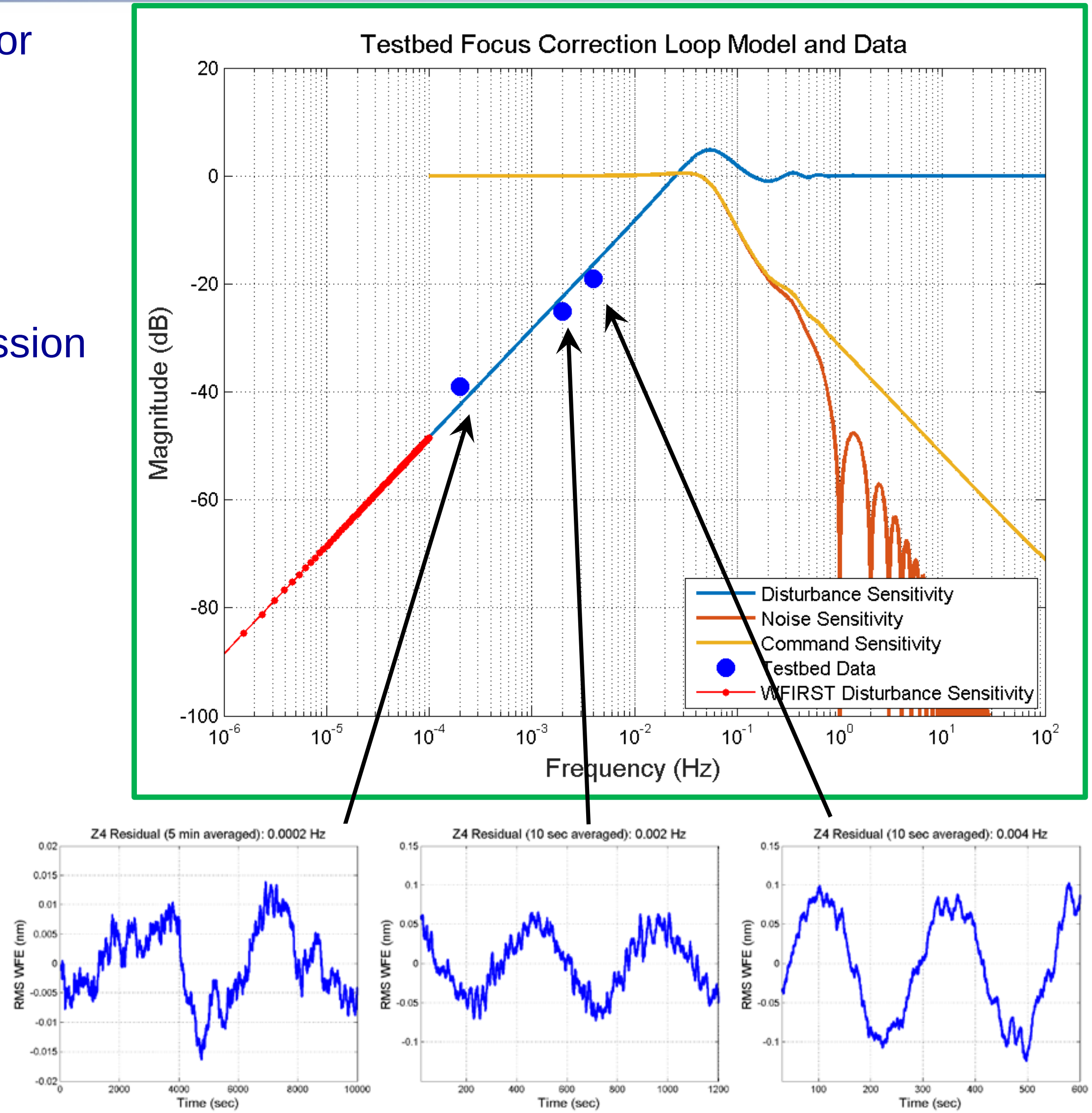


LoS correction loop performs well in both SPC and HLC modes

HLC LOWFS WFE Mode Correction: Focus

- Focus drift generated by OTA simulator
  - 2 nm P-V sinusoid, ~4x larger than flight
- DM #1 used to correct focus
- Testbed data matches control model prediction
- Projected WFIRST focus drift suppression is > 2 orders of magnitude
  - w/o LOWFS/C: Z4 drift ~ 0.5 nm (P-V)
    - Projected $\Delta C = 2.5\times10^{-9}$
  - w/ LOWFS/C: Z4 drift < 5 pm (P-V)





Residual Z4: 0.0002 Hz

Residual Z4: 0.002 Hz

Residual Z4: 0.004 Hz

MS 9 Dynamic Testing Conclusions

- Calibrated OTA simulator was used as the disturbance generator and to independently verify LOWFS sensor performance

- LOWFS sensor has demonstrated sensing of LoS tilt to the level of 0.2 mas (Milestone 6) and low order mode to the level of 12 pm rms

- LOWFS/C can maintain CGI contrast stability in presence of WFIRST LoS and low order WFE disturbances
  - Three modes (Z2, Z3, Z4) are the dominant disturbances for WFIRST
  - Correction greatly improves OMC contrast stability

- Simultaneous LoS and low order wavefront correction using both the FSM and DM were demonstrated
  - Closed loop LoS residual meets 0.5 mas rms per axis requirement for Cycle 5 (test) and Cycle 6 (model)
  - LoS error correction demonstrated for both HLC and SPC modes

Contrast Demonstration

Contrast level in new OMC testbed

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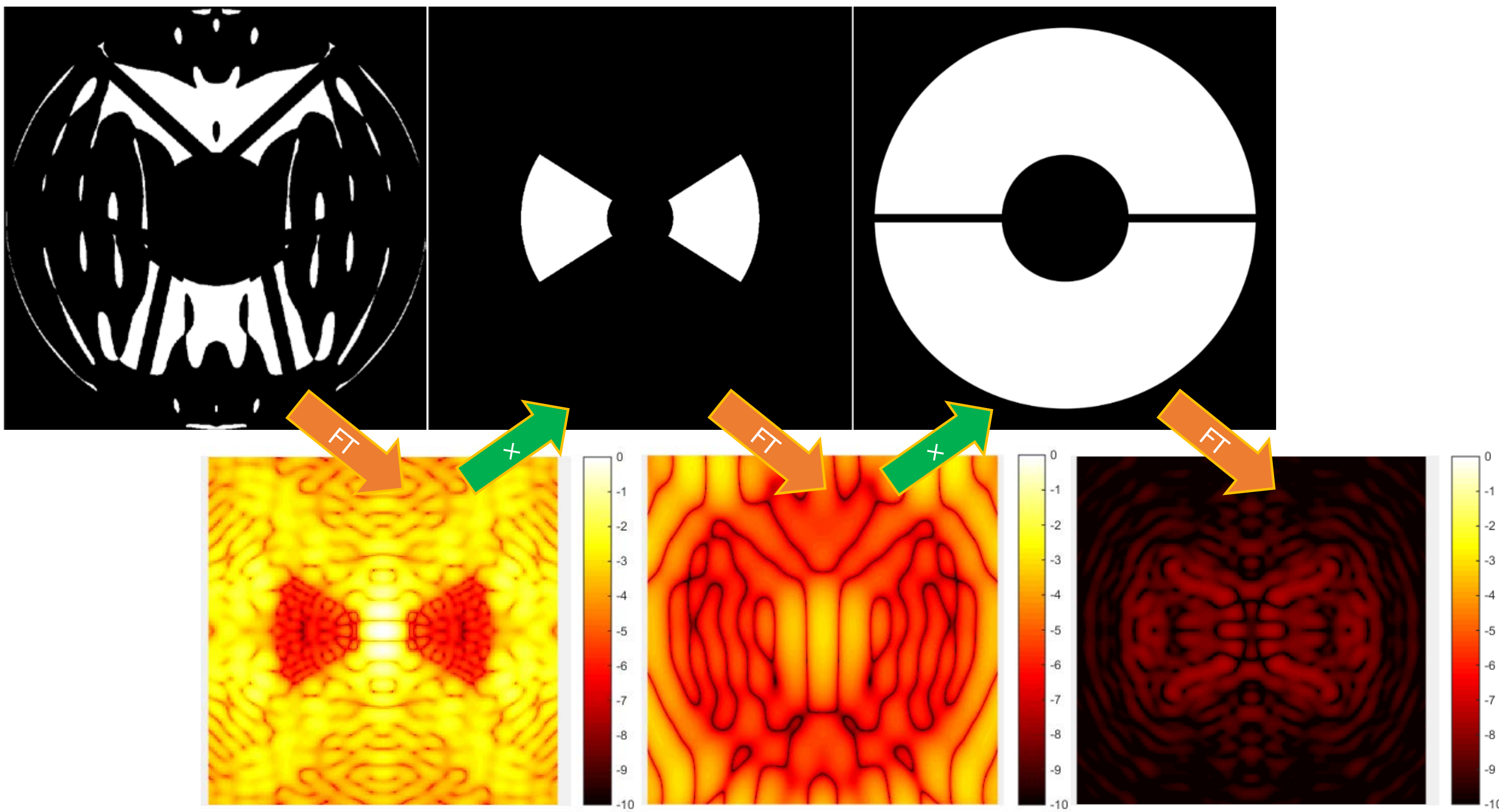
SPC Overview

Shaped pupil Lyot coronagraph (SPLC):

- Three coronagraphic elements: shaped pupil, bowtie, Lyot stop
- Need 3 sets of masks with different clocking orientations to cover full annulus
- Shaped pupil mask reoptimized for MCB to account for as-built OTA pupil and testbed magnification



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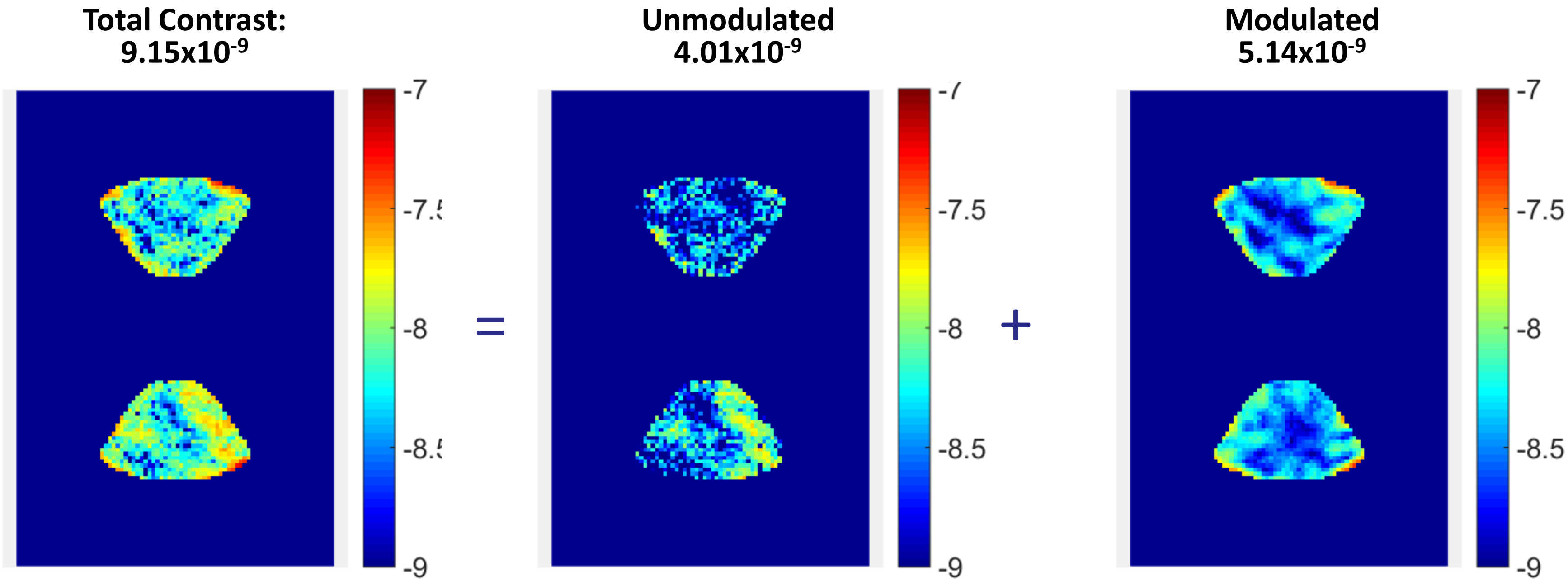
SPC Broadband Results



Performance:

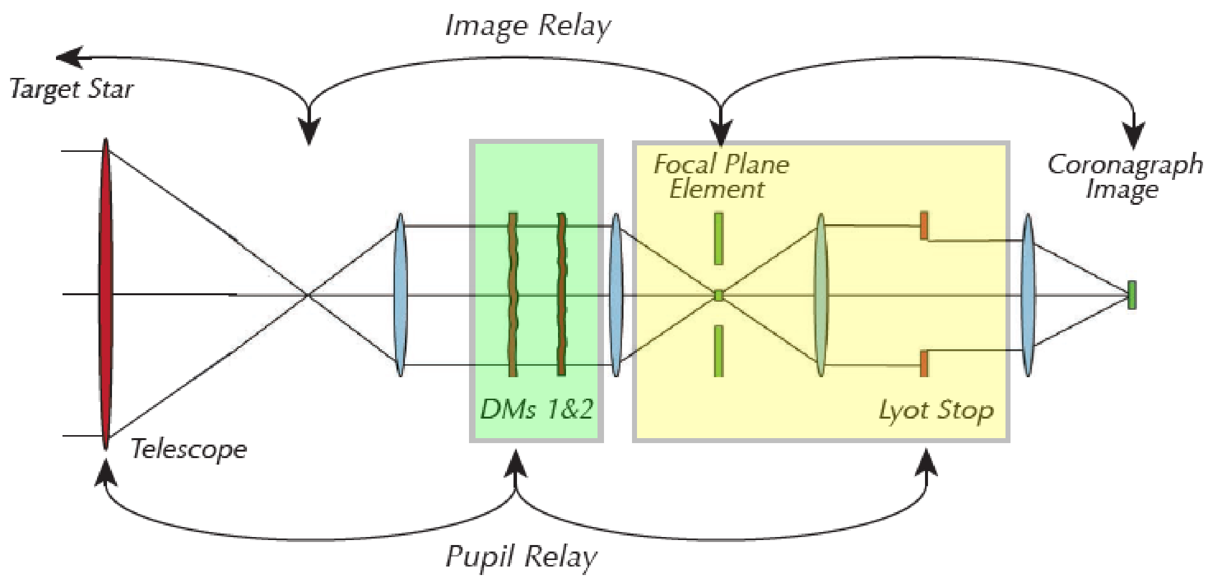
- **Average raw contrast: 9.15 × 10^{-9}**
- Accuracy: ± 5%

Configuration:

- 2.8 – 8.8 λ/D 2 x 65° dark hole
- 10% bandwidth centered at 550 nm
- Reflective black Si pupil mask
- New occulter with LOWFS feature fabricated using e-beam lithography
- 3 um pinhole pseudo-star (0.18 λ/D on sky)

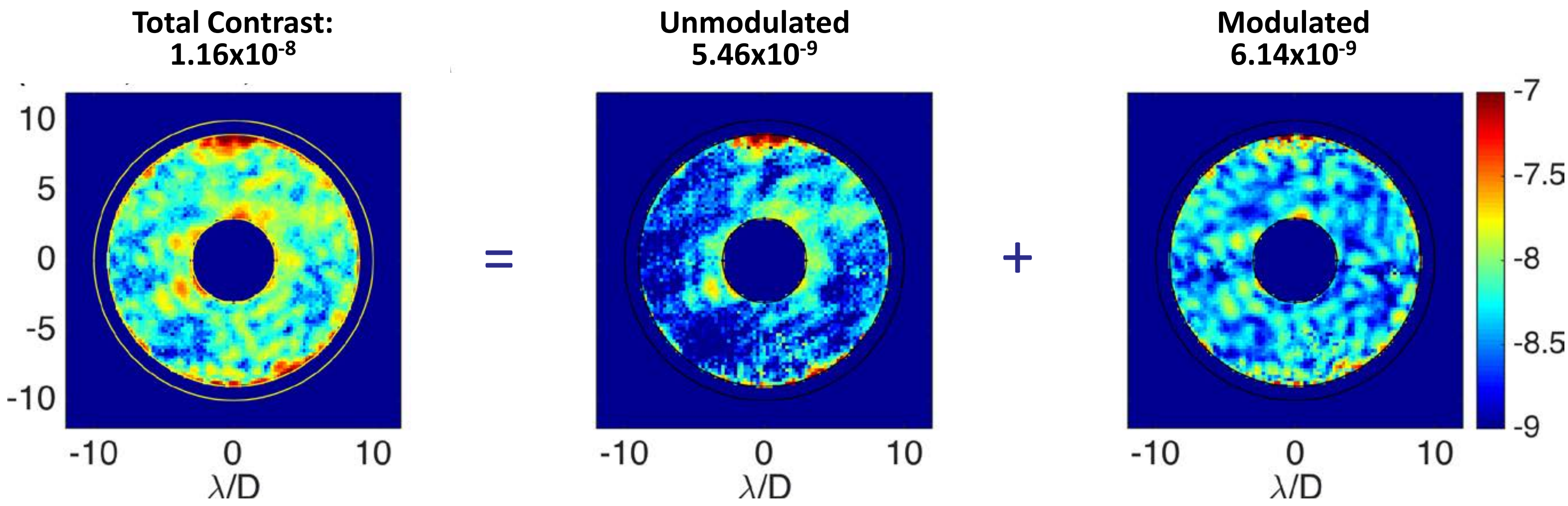
HLC Overview

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 DRM
- Essential elements:
  - 2 deformable mirrors
  - Focal plane occulting mask
  - Lyot stop

HLC Broadband Results

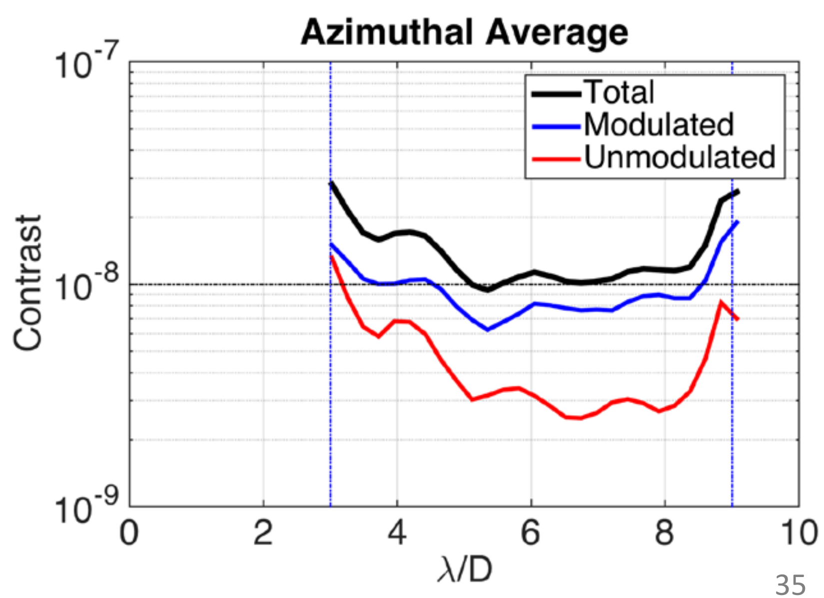


Performance:

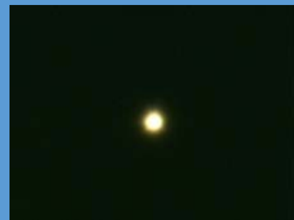
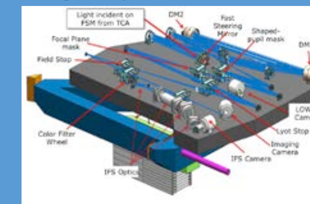
- **Average raw contrast: 1.16 × 10^{-8}**
- **Dominated by speckles ~OWA, reached 1x10^{-8} 3-8.8 λ/D**
- Accuracy: ± 5%

Configuration:

- 3 - 9 λ/D 360° dark hole
- 10% bandwidth centered at 550 nm
- Mask fabricated by e-beam lithography
- 3 um pinhole pseudo-star (0.18 λ/D on sky)



Unmodulated Light in HCIT and Flight

	Star 	Telescope 	Coronagraph 
Flight	- ~1 mas diameter - Spatially incoherent - Unpolarized	WFIRST OTA - Obscured pupil - f/1.2 primary	WFIRST OMC
Static testbeds	- SM fiber + 3 um pinhole - 10 mas diameter - Mostly spatially coherent - Unpolarized	- WFIRST obscuration only - f/30 illumination from pseudo-star	WFIRST HLC and SPC in separate testbeds
Early OMC testbed	- SM fiber + 3 um pinhole. - 40 mas diameter - Mostly spatially coherent - Polarization cross-terms	- Reverse WFIRST telescope simulator with f/1.2 primary - f/7 illumination from pseudo-star	WFIRST OMC

- Polarization/coherence related WF error in pseudo-star (fiber + pinhole) or OTA simulator were initially causing ~2×10^{-8} unmodulated OMC contrast floor
- Recently OMC went to “static style” front end (retaining LoS + focus dynamics) with good results
  - Polarization WF error in OTA w/o pseudo-star was modeled, expected to be a ~1e-9 contributor in the OMC testbed => early OMC pseudo star is the most likely culprit
- Work ongoing to understand the unmodulated light and build pseudo-star suitable for flight CGI

Model Comparison

Testbed achieved results consistent with model expectations?

Outline

- **Milestone 9 definition and result summary**
- **Dynamic OMC testbed overview**
- **Dynamic testing**
    - WFIRST on-orbit dynamic disturbance and LOWFS architecture
    - Pointing correction tests using FSM
    - Low order correction tests using DM
- **Contrast level in new OMC testbed**
    - Shaped pupil mode
    - Hybrid Lyot mode
    - Instrument contribution vs. GSE contribution
- **Model validation**
- **Simulated planet**
- **Summary**

Model Comparison Goal

- **For the flight system, we want to have a model good enough to predict the coronagraph performance in the essential areas**

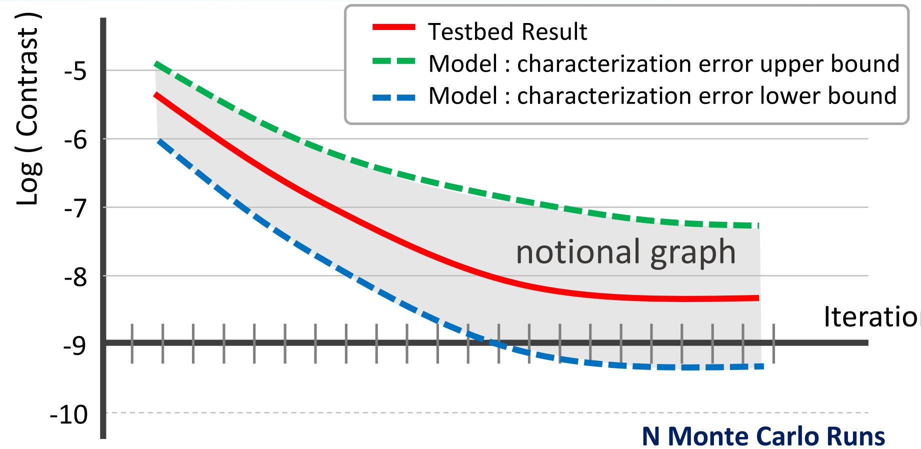
- **Important performance parameters are:**
  1. Contrast floor after wavefront control iterations are complete
  2. Contrast sensitivity to various system imperfections
  3. Number of iterations it takes to reach desired contrast and other important performance parameters will be studied post-milestone

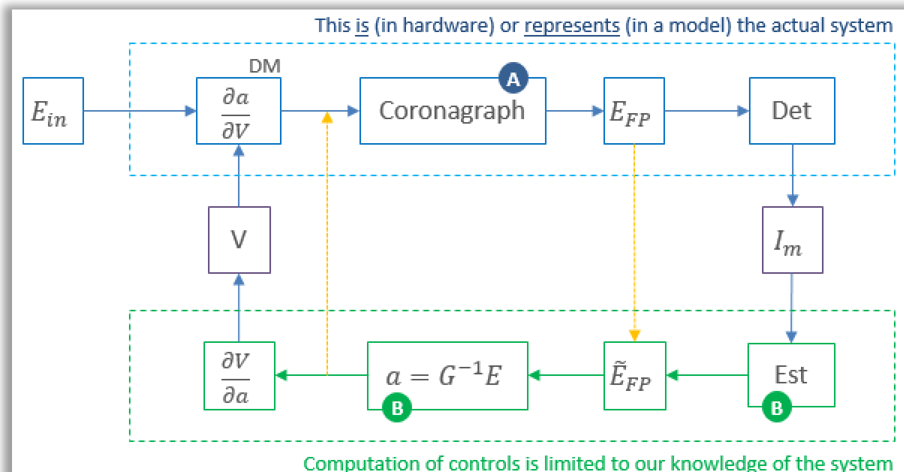
- **We consider our model validated if we can achieve model/testbed agreement of ~2X or better (MUF 2)**

- **For both HLC and SPC, extensive modeling has been done, and the results of those models have been compared with the testbed results**

Comparing Model with Testbed

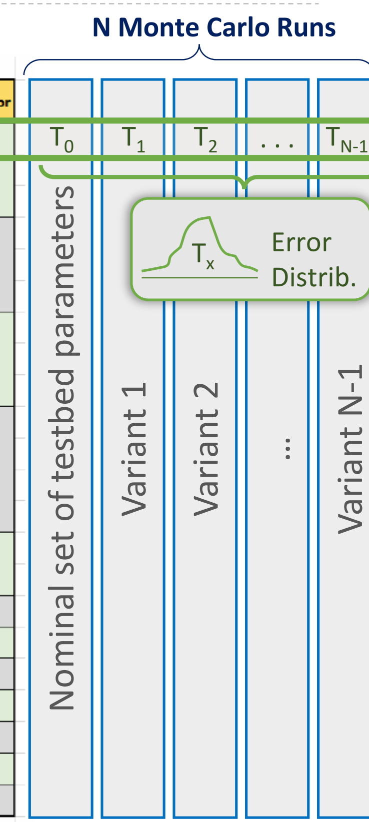
- Unlike passive optical instruments, coronagraph can effectively compensate for many deviations from design using DMs, as long as "as built" parameters are measured and captured in the control model
- In assessing model and testbed agreement, it is necessary to take into account knowledge errors about the state of the testbed
- This is done by varying the parameters in a Monte Carlo
- The control model is based on what is known, while the testbed model parameters are varied
- The distribution describing the knowledge error of each parameter is based on testbed experience.





MCB AdjustableParameters and Limits of Adjustment

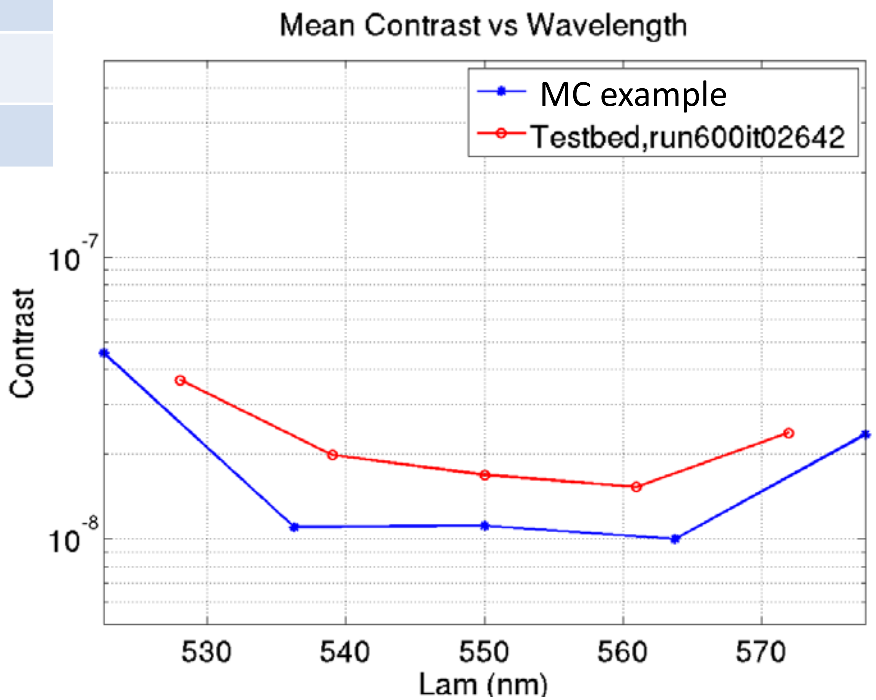
	Name	Range	Unit	Calibration Error
DM1	Tx	0	um	< 100um
	Ty	0	um	< 100um
	Rz	0	deg	< 0.5 deg
DM2	Tx	0	um	< 100um
	Ty	0	um	< 100um
	Rz	0	deg	< 0.5deg
Lyot	Tx	> 1	inches	< 100um
	Ty	> 1	inches	< 100um
	Rz			< 0.1 deg
Occ	Tx	> 1	inches	< 1.0um
	Ty	> 1	inches	< 1.0um
	Tz	> 1	inches	< 100um
	Rx/Ry	0	deg	< 5.0deg
Source	Tx	0		
	Ty	0		
Control Bands		1 - 5		
Control Bandwidth		2 - 10	%	
DH Area Location		Left half, etc		
DH Area Size		3-8, 3-9, etc		
DH Area Weighting		1, 2, 3, etc		
Camera	Tz	250	mm	
FSM	Rx/Ry	80	arc-sec	< 1e-6



SPC Model Comparison

	Modulated Contrast Component
Baseline Model Prediction	$5x10^{-9}$
Testbed Model Prediction	$1.5x10^{-8}$
Testbed Measured Result	$2x10^{-8}$

Note: Reflects 9/29/2016 testbed configuration, prior to OMC GSE update, hence higher contrast



For SPC mode, the key findings are:

- Typical known testbed imperfections do NOT limit the contrast floor, though they slow convergence
  - pupil WFE and amplitude error, DM gain & registration offset, etc.
- Most calibration errors, at current estimated levels, have minor impact on contrast
  - Examples: alignment errors, masks manufacture errors, and achromatic WFE
- Uncalibrated chromatic WFE (& spatial varying amplitude error), have larger impact and can limit SPC contrast floor if not accounted for in the model
  - Some aspects are specific to testing with a pseudo-star, less relevant for flight

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SPC Testbed Error Budget

		Design contrast	1.86E-09	2.01E-09	1.94E-09	2.31E-09	3.04E-09
		Delta E^2 (coherent)	2.78E-09	1.04E-09	1.01E-09	1.64E-09	3.09E-09
		Delta E^2 (incoherent)	3.66E-09	3.60E-09	3.60E-09	3.60E-09	3.62E-09
		Expected **mean** closed-loop contrast	8.30E-09	6.66E-09	6.54E-09	7.55E-09	9.75E-09
Alignment Knowledge Error							
SP x	32	um	2.10E-10	5.20E-11	4.40E-11	5.16E-11	9.79E-11
SP y	32	um	8.94E-11	3.52E-11	2.59E-11	2.90E-11	4.36E-11
SP clock	0.25	deg	1.51E-10	4.36E-11	3.50E-11	3.93E-11	5.29E-11
BT x	1	um	1.99E-11	5.03E-12	4.72E-12	6.84E-12	5.66E-12
BT y	1	um	2.43E-11	6.11E-12	3.57E-12	4.34E-12	1.03E-11
BT z	100	um	8.69E-12	2.35E-12	1.81E-12	2.42E-12	2.98E-12
BT clock	0.5	deg	8.34E-11	3.11E-11	2.13E-11	2.36E-11	3.49E-11
LS x	32	um	2.69E-12	1.60E-12	8.91E-13	1.86E-12	2.57E-12
LS y	32	um	1.64E-12	6.10E-13	4.70E-13	4.14E-13	7.22E-13
LS clock	0.5	deg	1.38E-13	4.58E-14	2.68E-14	2.09E-14	7.51E-14
DM1 x	0.075	mm	4.19E-11	1.82E-11	1.51E-11	1.29E-11	1.71E-11
DM1 y	0.075	mm	4.03E-11	1.50E-11	1.15E-11	1.14E-11	1.49E-11
DM1 clock	0.03	deg	4.52E-13	1.64E-13	1.28E-13	1.43E-13	1.96E-13
DM1 z	5	mm	7.18E-15	7.23E-15	7.00E-15	6.82E-15	6.78E-15
DM2 x	0.075	mm	2.18E-11	1.13E-11	8.04E-12	8.19E-12	1.20E-11
DM2 y	0.075	mm	1.53E-11	7.41E-12	5.31E-12	5.04E-12	6.09E-12
DM2 clock	0.03	deg	2.14E-13	9.24E-14	7.62E-14	7.06E-14	8.66E-14
DM2 z	5	mm	1.47E-14	1.37E-14	1.27E-14	1.19E-14	1.16E-14
BT obliquity	1	deg	4.43E-15	4.29E-15	5.26E-15	3.29E-15	2.06E-15
Source X	0.5	pix	7.15E-11	1.82E-11	1.66E-11	2.14E-11	3.26E-11
Source Y	0.5	pix	1.04E-10	3.15E-11	2.77E-11	3.50E-11	4.75E-11
Manufacturing Knowledge Error							
SP undercut	1	um	2.93E-11	8.01E-12	7.62E-12	1.53E-11	2.34E-11
BT inner radius	1	um	8.88E-11	9.62E-11	1.26E-10	2.10E-10	4.10E-10
BT outer radius	1	um	1.02E-10	1.48E-10	2.72E-10	5.45E-10	1.07E-09
BT angle	0.1	deg	1.27E-10	1.27E-10	1.29E-10	1.22E-10	1.11E-10

Global Static Wavefront Knowledge Error							
Z4 (phase)	0.05	rad rms	1.08E-11	2.93E-12	2.26E-12	2.99E-12	3.68E-12
Z5 (phase)	0.05	rad rms	2.67E-11	6.29E-12	4.65E-12	8.48E-12	1.10E-11
Z6 (phase)	0.05	rad rms	1.57E-11	4.91E-12	3.17E-12	4.60E-12	8.26E-12
Z7 (phase)	0.05	rad rms	2.24E-11	3.82E-12	4.42E-12	4.45E-12	6.31E-12
Z8 (phase)	0.05	rad rms	1.17E-11	2.88E-12	2.73E-12	2.21E-12	6.20E-12
Z2 (amp)	2	% rms	2.24E-11	1.12E-11	1.03E-11	8.91E-12	2.08E-11
Z3 (amp)	2	% rms	3.70E-11	9.26E-12	7.18E-12	9.97E-12	2.00E-11
Z4 (amp)	2	% rms	3.75E-10	1.40E-10	1.35E-10	1.67E-10	2.08E-10
Chromatic Static Wavefront Knowledge Error							
Z5 phase from pol (+/- to ends of band)	0	rad rms	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z6 phase from pol (+/- to ends of band)	0	rad rms	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Z2 amp from pinhole (+/- to ends of band)	2	% rms	3.59E-10	6.72E-11	3.62E-11	9.80E-11	2.60E-10
Z3 amp from pinhole (+/- to ends of band)	2	% rms	6.64E-10	1.34E-10	4.44E-11	1.84E-10	5.44E-10
Estimated Static Terms							
OTA polarization (via J. McGuire)	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jitter/Drift							
Source X	0.11	pix	4.94E-10	4.57E-10	4.63E-10	4.75E-10	4.93E-10
Source Y	0.14	pix	2.23E-09	2.18E-09	2.14E-09	2.10E-09	2.04E-09
Z4	0.5	nm rms	6.84E-10	7.03E-10	7.23E-10	7.48E-10	7.80E-10
Z5	0.1	nm rms	9.73E-12	9.71E-12	9.70E-12	9.86E-12	1.03E-11
Z6	0.1	nm rms	3.83E-12	3.61E-12	3.31E-12	3.11E-12	3.05E-12
Z7	0.1	nm rms	1.51E-10	1.64E-10	1.79E-10	1.96E-10	2.17E-10
Z8	0.1	nm rms	9.25E-11	8.38E-11	7.82E-11	7.62E-11	7.62E-11

- SPC error budget based on compact model (Fourier-based with minimal Fresnel terms)
- Empirical validation of terms where feasible (tilts, offsets, static wavefronts)
- Testbed and model contrast are within MUF = 2

HLC Model Comparison

Levels of HLC model fidelity

	Includes Representative Testbed Calibration Errors (between testbed parameters and their representation in the control model)	Includes Testbed Validated Regularization Approach (vs. ideal regularization that causes testbed to diverge due to imperfect calibration)
Model I	No	No
Model II	No	Yes
Model III	Yes	Yes

High level modulated light decomposition:

		Model Prediction	Testbed Contrast
Modulated light		1.02E-08	6.14E-09
M1	Baseline with optimal operation	2.00E-10	
M2	Baseline with testbed-like operation	3.88E-09	
M3	Operational algorithm delta	2.75E-09	
M4	Calibration error delta	3.60E-09	

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HLC Testbed Error Budget (1/2)

Testbed Performance				1.16E-08
	Unmodulated		5.46E-09	
	Modulated		6.14E-09	
Model Prediction				1.38E-08
Unmodulated light			3.57E-09	
U1	Pseudo-star illumination*	8.48E-10		
U2	Jitter (> 0.2 Hz)			
	LoS Jitter	1.09E-09		
	Focus Jitter	1.00E-10		
	Higher order Jitter	<1.00E-11		
	Pupil/Lyot Stop Jitter			
U3	Occulter ghost	1.00E-09		
U4	Polarization	<1.00E-11		
U5	source/pupil lens ghost	<1.00E-11		
U6	Estimation error	5.00E-10		
U7	Stray & background light	<1.00E-11		
Modulated light			1.02E-08	
	Baseline with optimal operation	2.00E-10		
	Baseline with TB operation	3.88E-09**		
	Operation algorithm	2.75E-09**		
	Miscalibration	3.60E-09		

11/01/2016 OMC Testbed Configuration

* Empirically extrapolated, not physically modeled. Not relevant for flight

** Modeled parameters not fully optimized, hence modulated result is more conservative than testbed data

HLC Testbed Error Budget (2/2)

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WFIRST

- Grayed-out rows: accounted for in MC study
- Empty rows: not studied yet, low sensitivities

Level 4	Contrast		
Miscalibration Total			3.60E-09

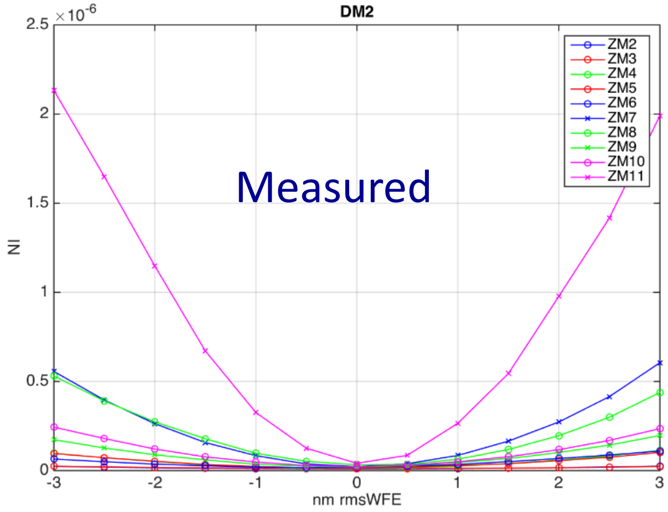
Monte-Carlo Analysis (major errors)			1.50E-09
S1	Initial WFE Estimation error (epup WFE error)		
	Phase Retrival Error		
	Phase Retrieval Repeatibility Error		
	Phase Distribution Error		
S2	Initial Amplitude Estimation Error (=epup amplitude error)		
	Phase Retrival Error		
	Wavelength dependency		
	Amplitdue distribution Error		
S4	HLC FPM Mask (occulter) Alignment		
	x		
	y		
	z		
	Tip or Tilt		
S5	DM1 & DM2 actuator registration		
	x and y		
	DM Z location		
S8	Lyot stop mask alignmnent (to AFTA obscuration in x/y/Rz, to pupil in Rx/Ry/z)		
	calibration x		
	calibration y		
	calibration clocking		
	calibration z		

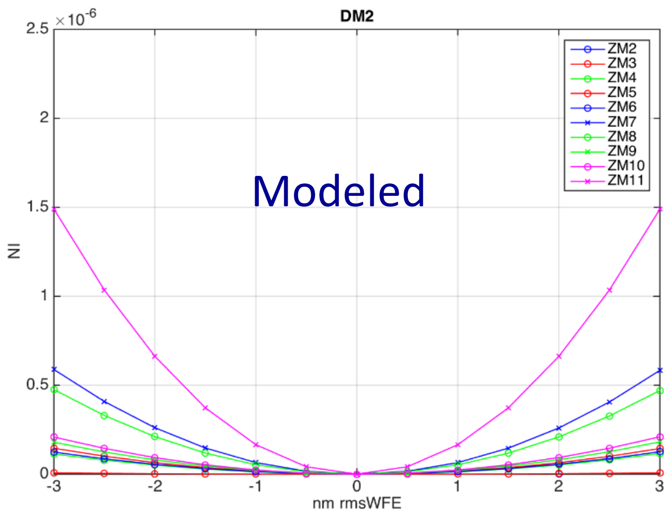
Static			2.08E-09
S1	Initial WFE Estimation error (epup WFE error)		
	Phase Retrival Error		
	Phase Retrieval Repeatibility Error		
	Phase Distribution Error	1.00E-09	
S2	Initial Amplitude Estimation Error (=epup amplitude error)		
	Phase Retrival Error		
	Wavelength dependency	1.00E-11	
	Amplitdue distribution Error		
S3	HLC FPM Mask (occulter) Fabrication error		
	NI OD bias	1.00E-11	
	NI OD calibration error	1.00E-11	
	NI diameter bias		
	NI diameter calibration error		
	Dielectric off center		
	Dielectric optical height error		
	Other Dielectric error		
	substrate defects		
S4	HLC FPM Mask (occulter) Alignment		
	x		
	y		
	z	1.00E-11	
	Tip or Tilt		
S5	DM1 & DM2 actuator registration		
	x and y		
	DM Z location		
S6	DM actuator calibration		
	influence function match		
	influence function variation		
		5.00E-10	

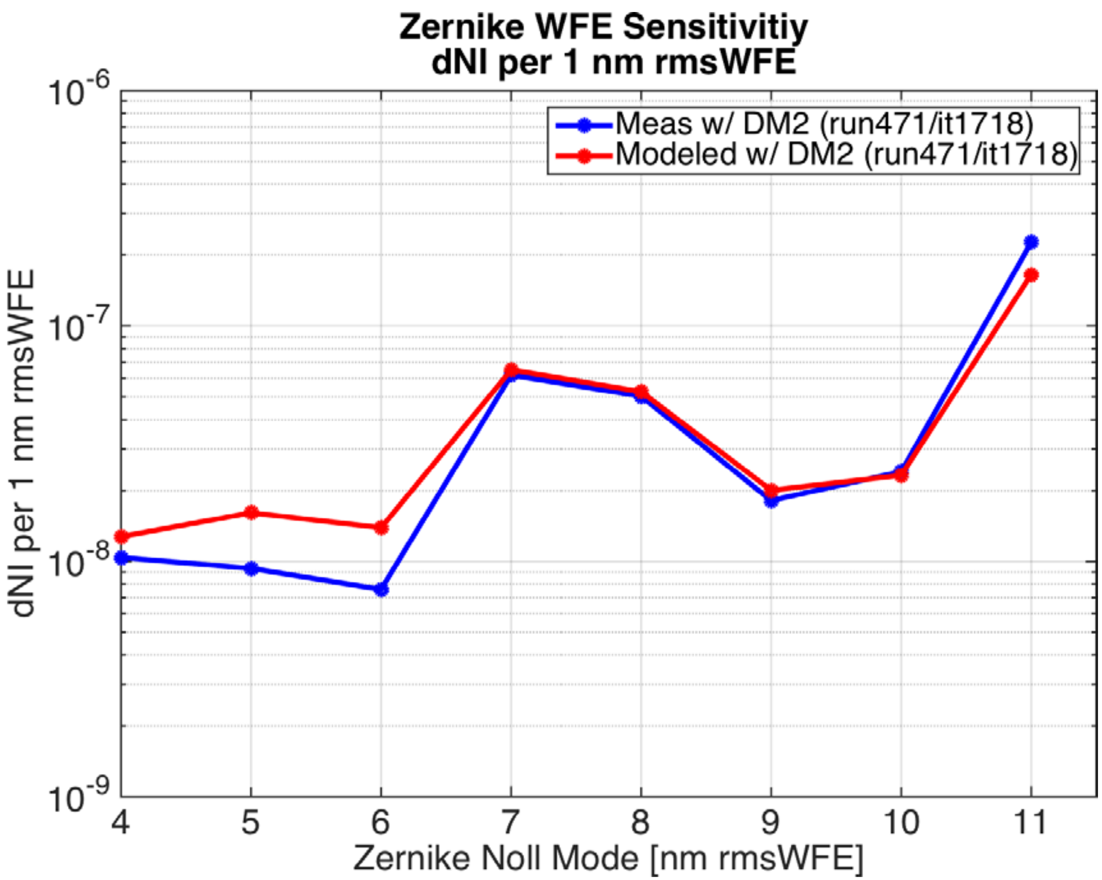
	DM Gain Calibration Uncertainty		
	non-functional actuators		
S7	Lyot stop mask calibration error	1.00E-11	
S8	Lyot stop mask alignmnent (to AFTA obscuration in x/y/Rz, to pupil in Rx/Ry/z)		
	calibration x		
	calibration y		
	calibration clocking		
	calibration z		
S9	Star Source Spectrum		
	Pass band slope		
	Stop band rejection	1.00E-11	
S10	Plate Scale Calibration	1.00E-11	
S11	Plate Scale Distortion		
S12	Detector Noise & Calibration	1.00E-11	
	Dark level (std)		
	White noise		
S13	Photometric error	5.00E-10	
Dynamic			2.00E-11
D2	Drift error (Any drift smaller than 0.2 Hz)		
	Star Drift		
	FFM Drift		
	Lyot Stop Drfit		
	LOWFE Frift		
D3	DM performance-hysteresis	1.00E-11	
D4	DM performance-repeatability	1.00E-11	
D5	Laser power changes (photometric error)		
D5	Laser spectrum changes		

Detailed testbed error budgets exist for HLC and SPC

HLC Zernike WFE sensitivities: Test vs. Model







Good match between model predicted and testbed measured sensitivities to low order wavefront errors

Model Validation Results

- **The knowledge errors, particularly chromatic errors, have a significant impact on the best achieved contrast**
- **We see agreement, to better than factor of 2, in predicting**
  - Contrast floor
  - Contrast chromaticity
  - Contrast wavefront sensitivity
- **Detailed testbed error budgets are in place for both SPC and HLC modes of OMC**
- **Validated models provide guidance in regard to improving testbed and flight instrument characterization and operation**

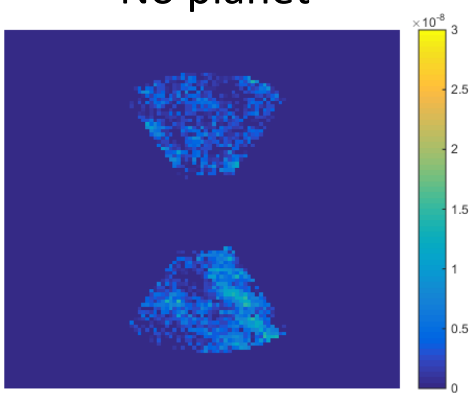
Outline

- **Milestone 9 definition**
- **Dynamic OMC testbed overview**
- **Dynamic testing**
  - WFIRST on-orbit dynamic disturbance and LOWFS architecture
  - Pointing correction tests using FSM
  - Low order correction tests using DM
- **Contrast level in new OMC testbed**
  - Instrument contribution vs. GSE contribution
  - Hybrid Lyot mode
  - Shaped pupil mode
- **Simulated planet**
- **Summary**

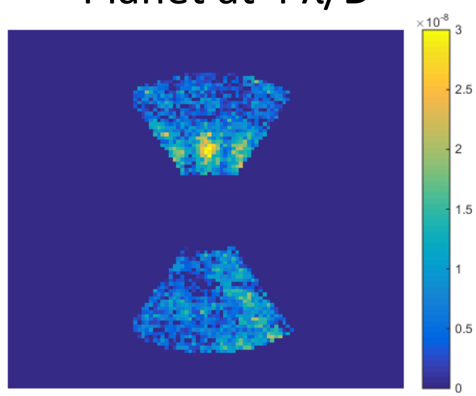
Planet Simulation

- **Create a pseudo planet near the star that is incoherent with the main beam, see if you can pick it out from probe images**
- **We choose to make the source incoherent by temporal separation: image planet and star at different times**
  - Currently doing this with separate images
  - Could do same image by adding external shutter, but benefit seems small
  - Add a separate planet image to each probe image; let estimation handle the extraction
- **Drive planet location by moving star with jitter mirror**
  - Enough JM stroke for ±7.2 λ/D (at 550 nm)

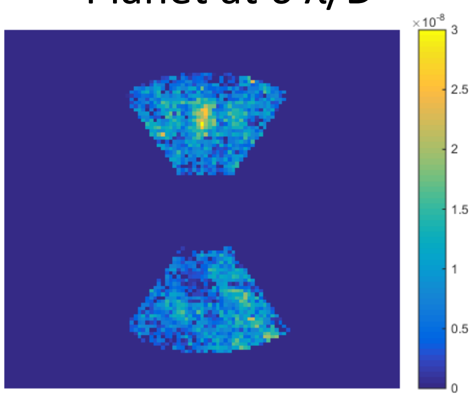
No planet



Planet at 4 λ/D



Planet at 6 λ/D



Milestone 9 Summary

- **Completed and commissioned the new OMC testbed including:**
  - Dynamic OTA simulator with WFIRST obscuration
  - OMC coronagraph bench switchable between SPC and HLC modes
  - LOWFS/C subsystem for sensing and correcting pointing errors and low order drifts
- **Successfully carried out OMC LOWFS/C dynamic test program:**
  - Pointing error suppression
  - Low order wavefront drift correction with a deformable mirror
- **Optically added a simulated planet**
- **OMC testbed error budget and model validation program, demonstrated model/testbed agreement within a factor of 2**
- **OMC testbed has demonstrated < 1×10^{-8} broadband contrast in SPC mode**
  - After recent front end reconfiguration (pseudo-star + mini telscope)
  - HLC mode is nulling now, current result ~1×10^{-8}