Jet Propulsion Laboratory
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WFIRST Coronagraph Low Order Wavefront Sensing and Control Dynamic Demonstration

F. Shi, E. Cady, B.-J. Seo, X. An, K. Balasubramanian, B. Kern, R. Lam, D. Liu, C. Mejia Prada, D. Moody, K. Patterson, I. Poberezhskiy, A.J.E. Riggs, D. Ryan, J. Shields, H. Tang, J. Trauger, T. Truong, R. Zimmer, D. Wilson

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California 91109

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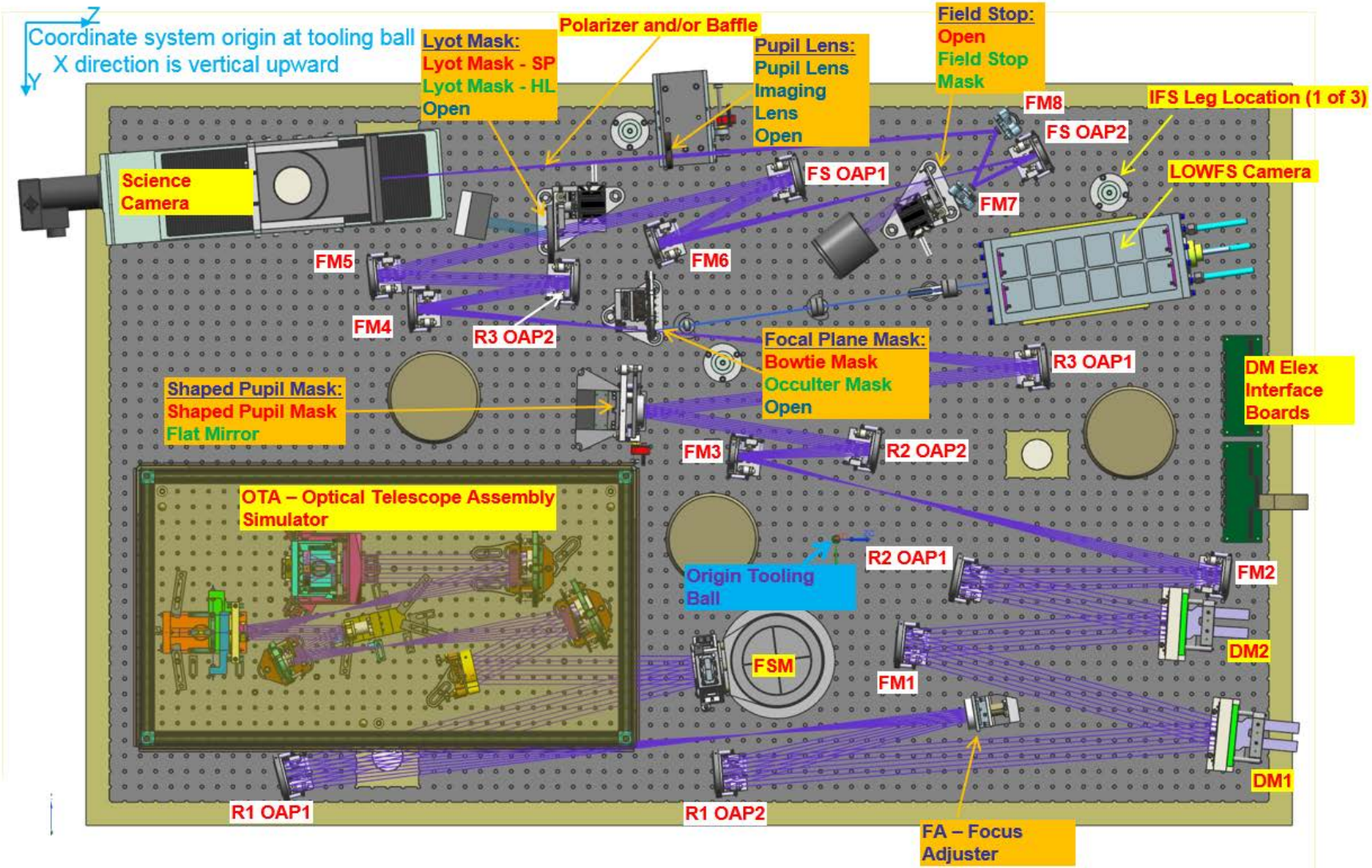
OMC Dynamic Testbed

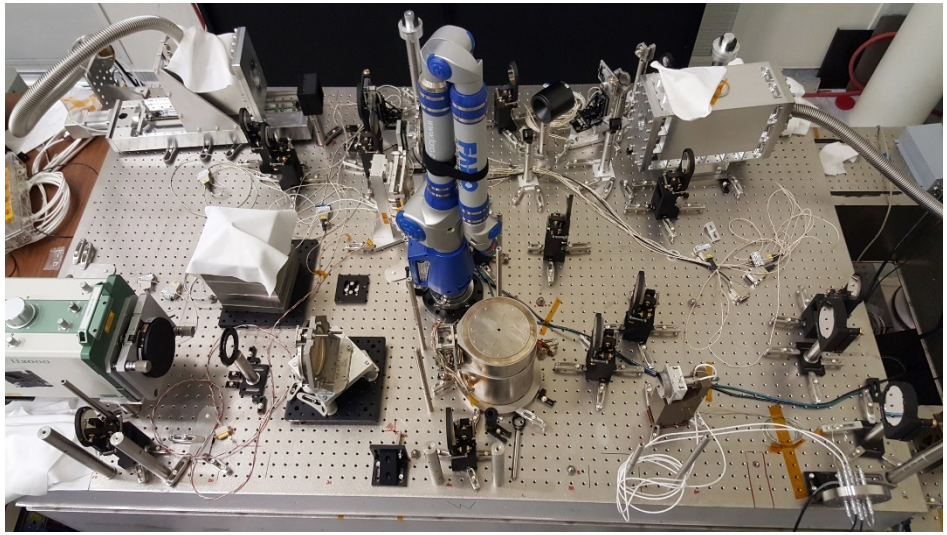
- **Completed and commissioned advanced testbed that introduces many new features for high fidelity testing of space coronagraphs:**
  - New masks and stops for two coronagraph modes (Shaped Pupil and Hybrid Lyot) on the same testbed – similar to WFIRST flight coronagraph instrument – with mechanisms 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

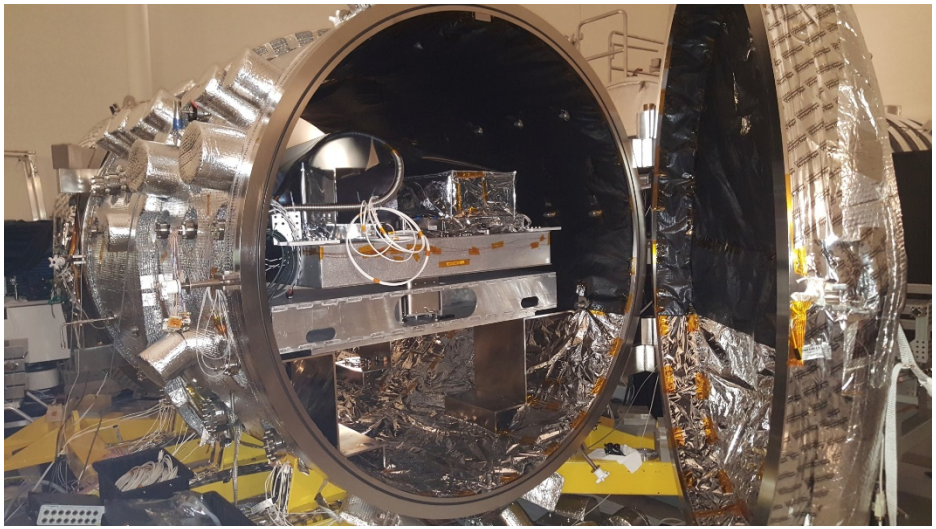
OMC Dynamic Testbed

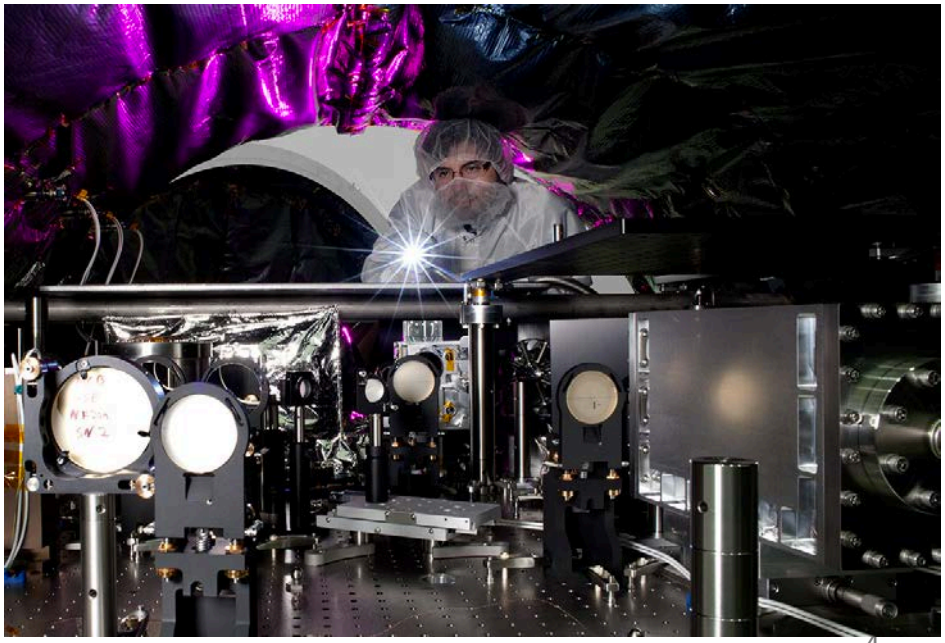


Mechanisms in Orange boxes: red is shaped-pupil mode and green is hybrid Lyot mode
Table is invar 78" x 48"

OMC Dynamic Testbed



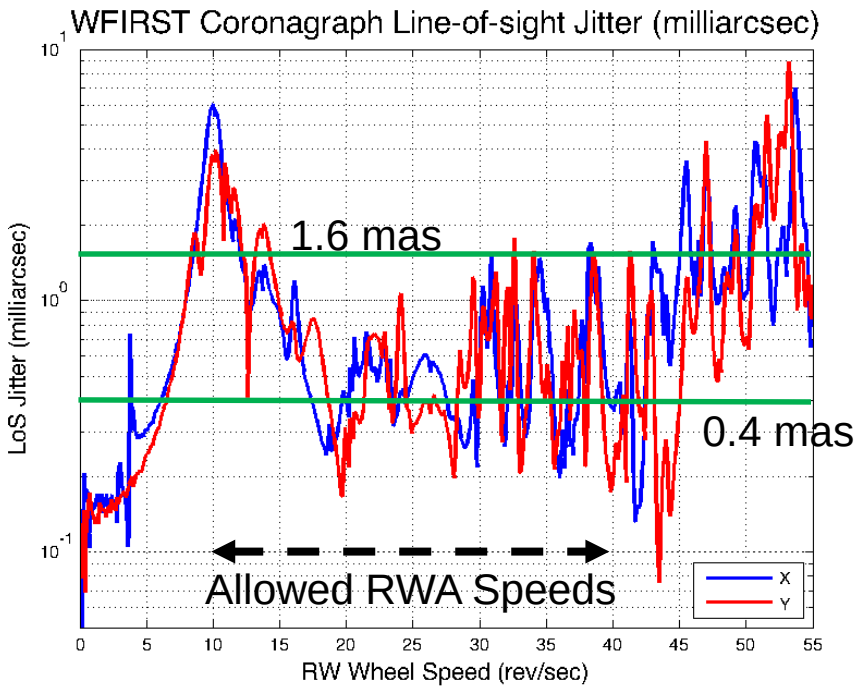




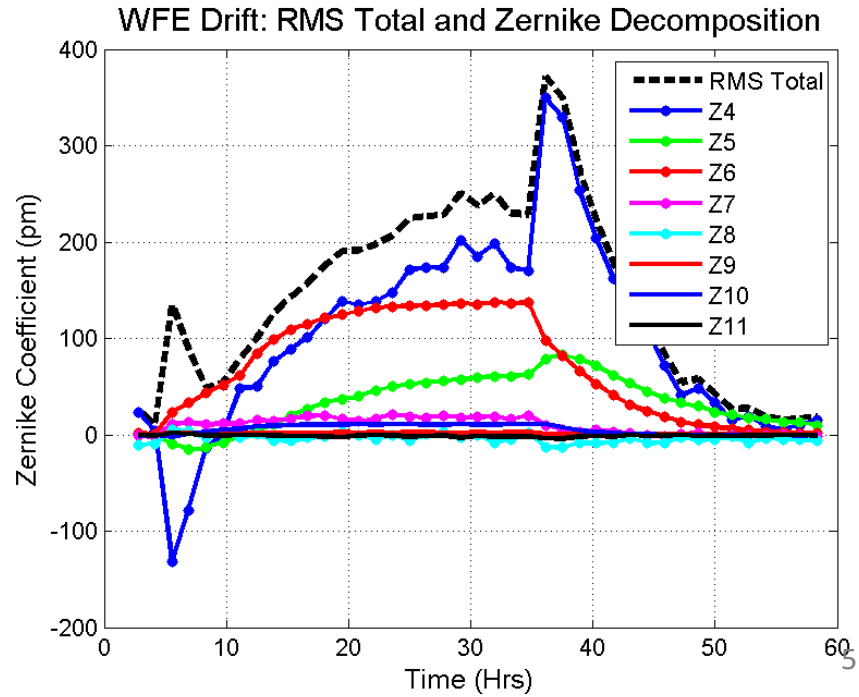
WFIRST Telescope LoS Jitter and WFE Drift

- **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).

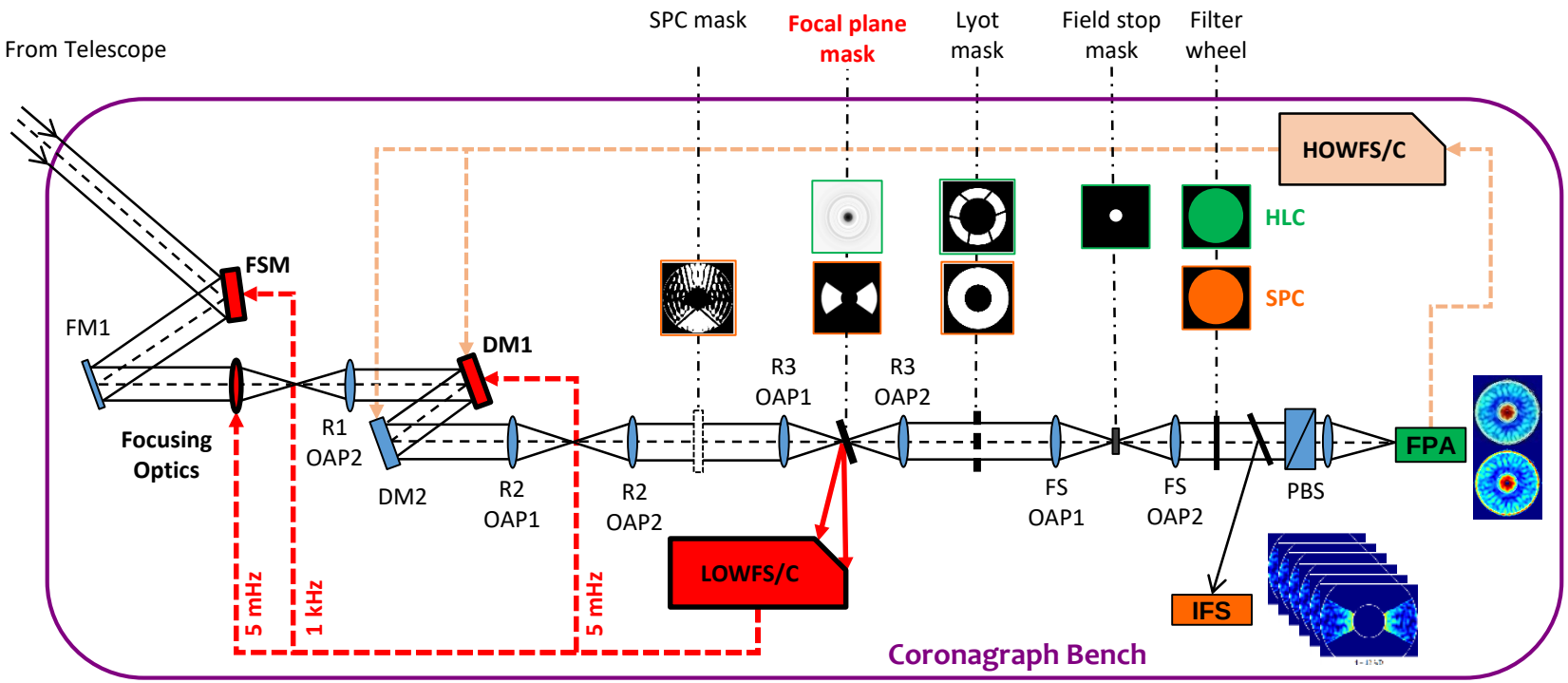
LoS vs RWA Speed



WFE Drift



LOWFS/C Overview

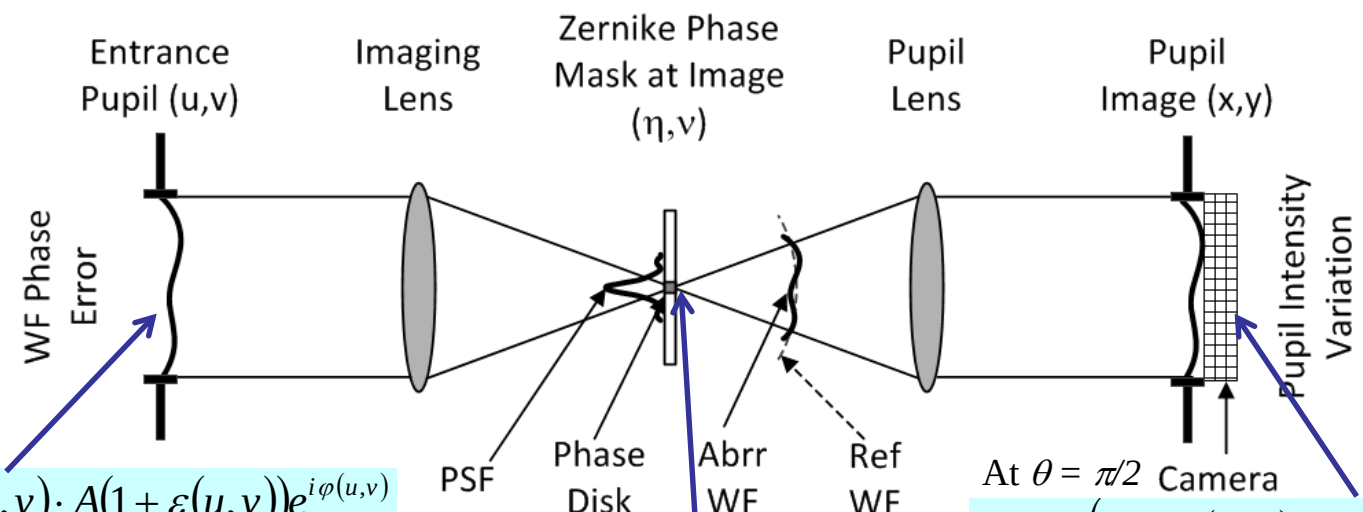


- LOWFS/C subsystem measures and controls line-of-sight (LoS) jitter and drift as well as the thermally induced low order wavefront drift
- Differential sensor referenced to coronagraph wavefront control: maintains wavefront established for high contrast (HOWFS/C)
- Uses rejected starlight from occulter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

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 π/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**



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

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

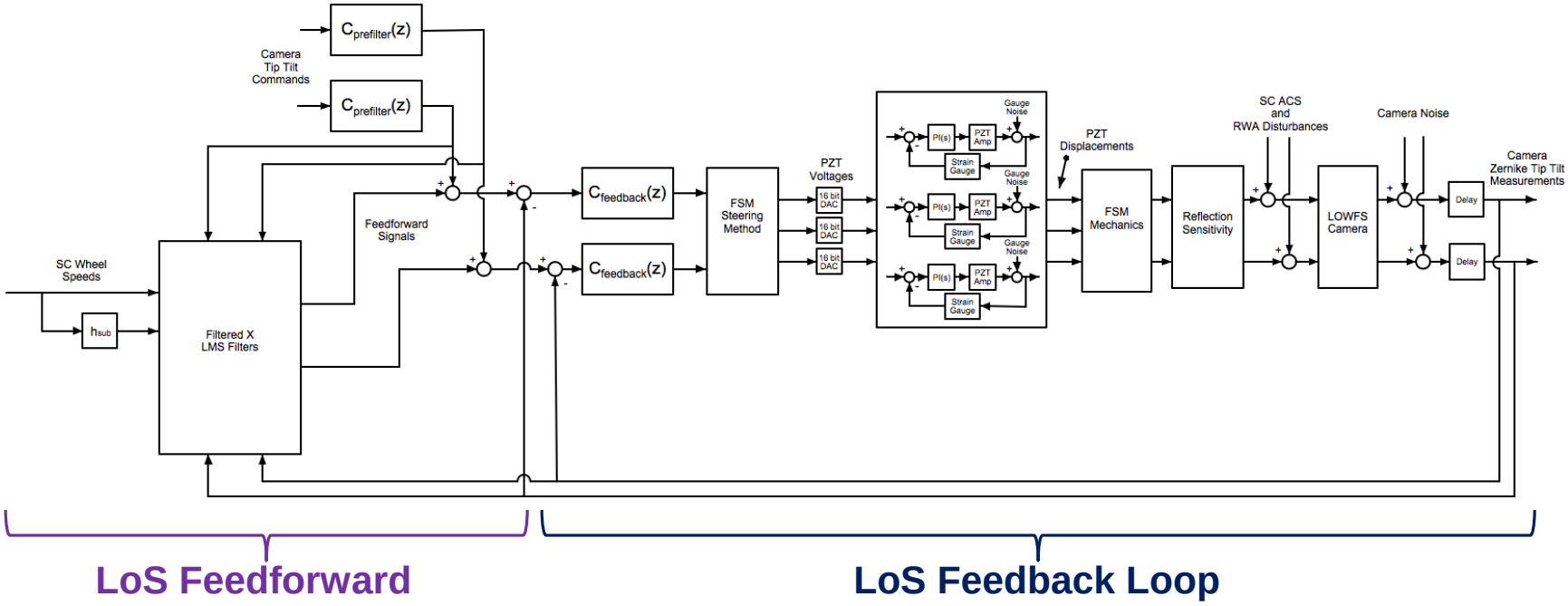
$$\hat{E}(\eta,\upsilon) = A\cdot CPSF(\eta,\upsilon)e^{i\theta} + A\cdot CPSF(\eta,\upsilon)\otimes F\{\varepsilon(u,v)+i\varphi(u,v)\}$$

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

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

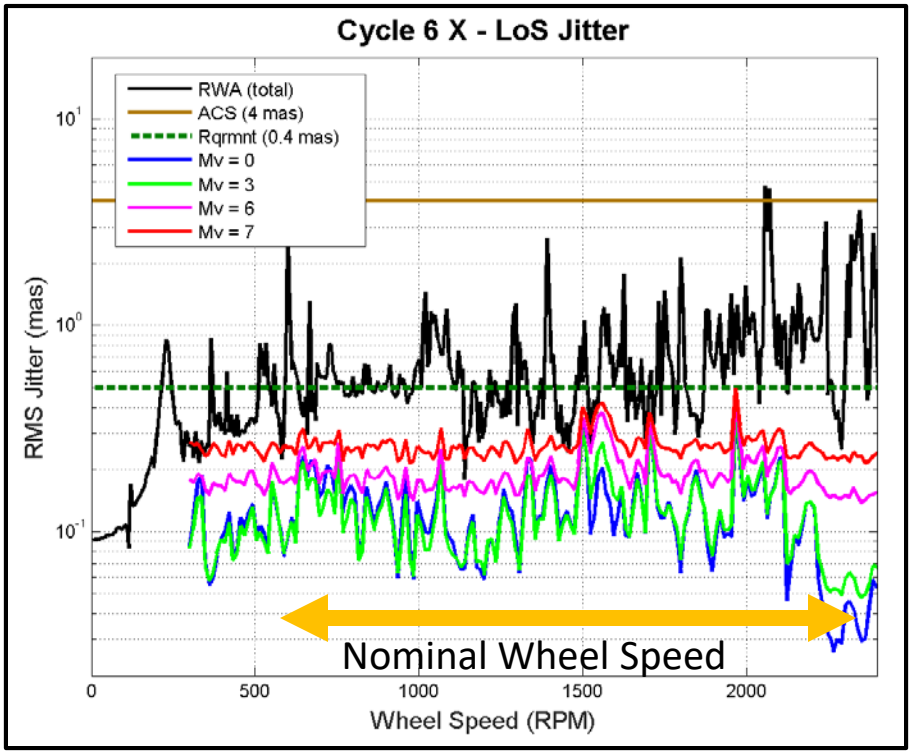


Modeling LoS Correction w/Cycle 6 Input

- **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**

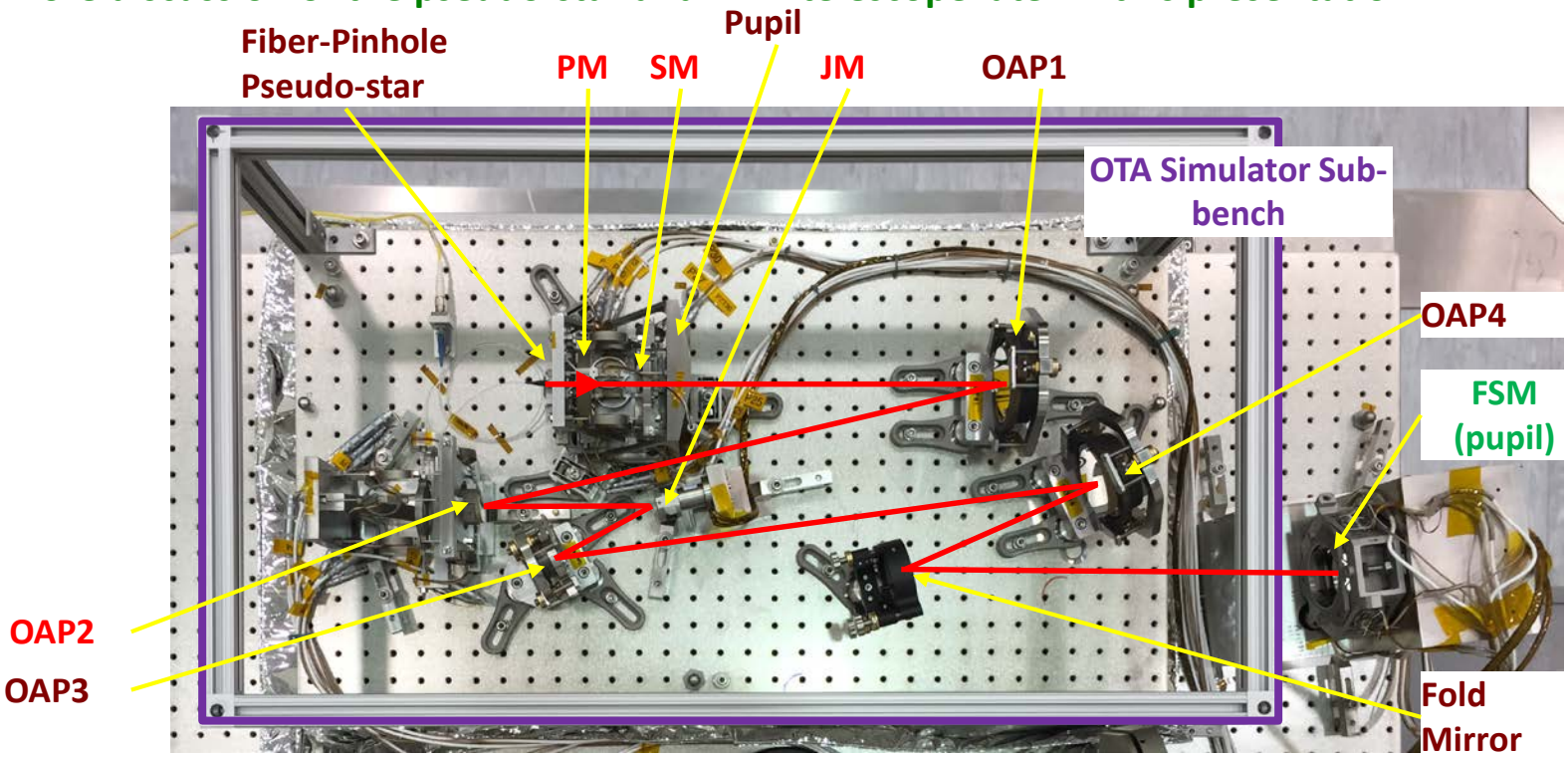
X jitter residual over 10 - 40 rev/sec (600 - 2400 rmp)			
Star Mv	< 0.4	< 0.8	< 1.6
0	99.30%	100%	100%
3	99.30%	100%	100%
6	99.30%	100%	100%
7	97.40%	100%	100%

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%

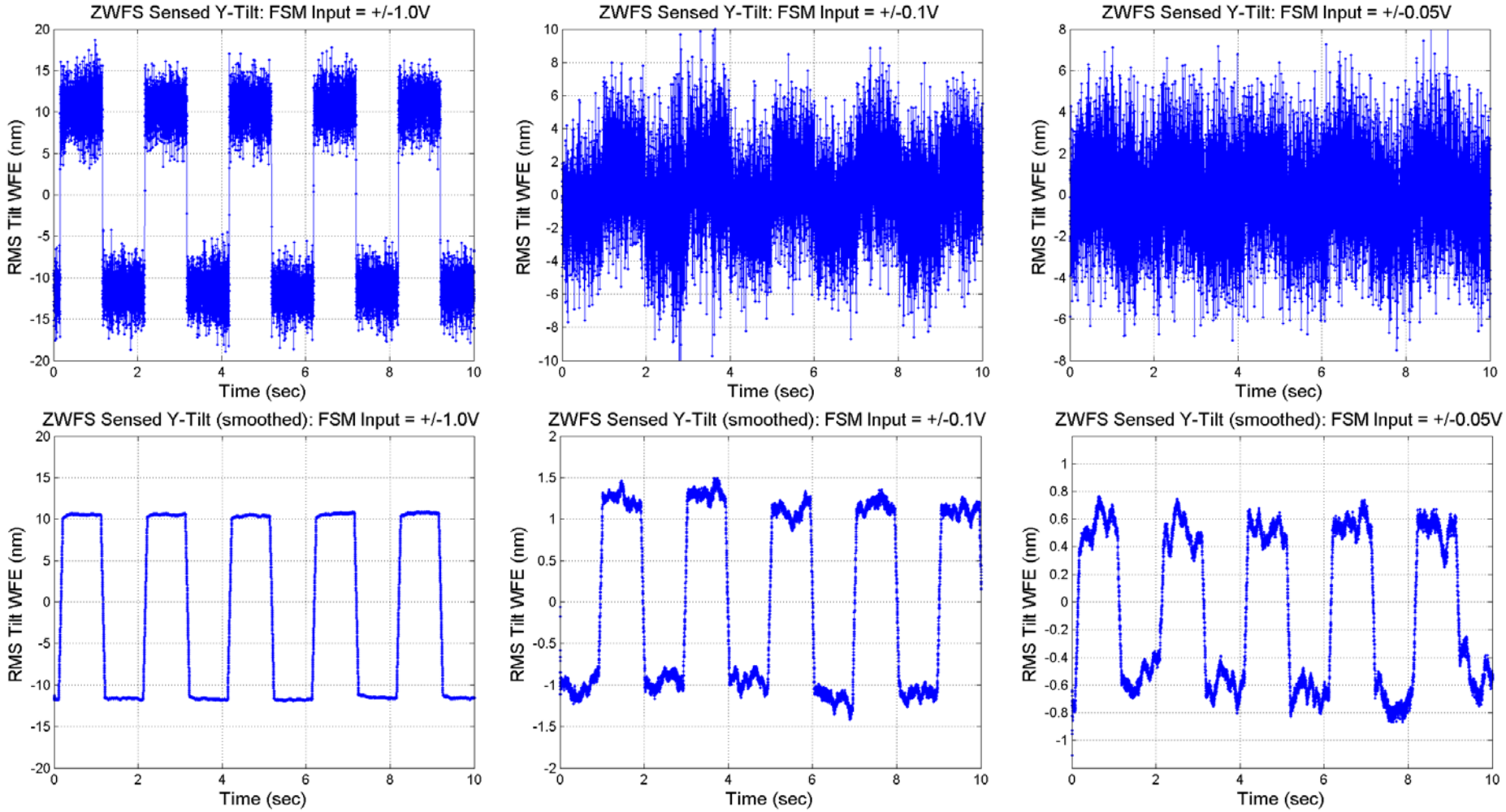


OTA Simulator for OMC Testbed

- **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**



ZWFS Results: Line of Sight Error Sensing



Mean Sep=22.1 nm=7.7 mas

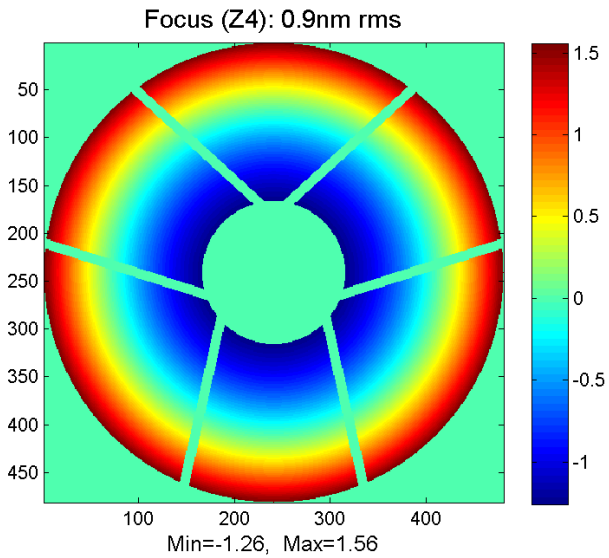
Mean Step=2.2 nm=0.77 mas

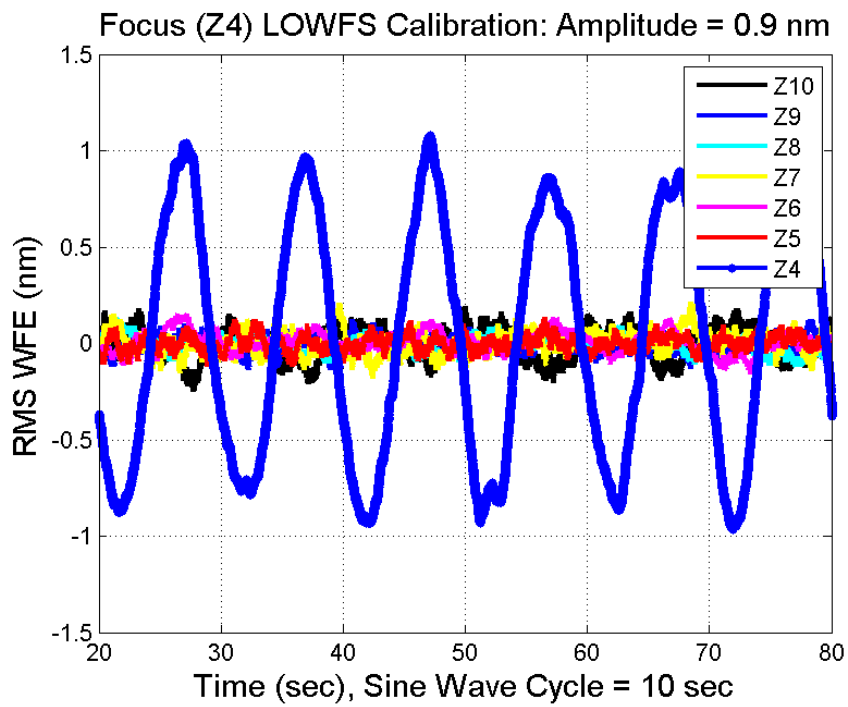
Mean Step=1.2 nm=0.38 mas

- Sensor clearly detects +/- 0.19 mas on-sky signal (right column)
- ZWFS sensed tilt WFE matches calibrated input to within 8%

ZWFS Calibration: Focus

- **OTA Simulator generates sinusoidal focus mode (Z4) with PZT-induced telescope motion**
- **Input DAC amplitude 0.2 V is equivalent to 0.9 nm from OTA-S Zygo calibration**
- **LOWFS sensed applied focus (Z4) disturbance**
  - Camera running at 500 Hz, Exp = 0.3 ms. FSM feedback loop closed
  - LOWFS sensor data averaged (1 sec box car) to remove the detector noise
- **The cross talk among low order modes is small**

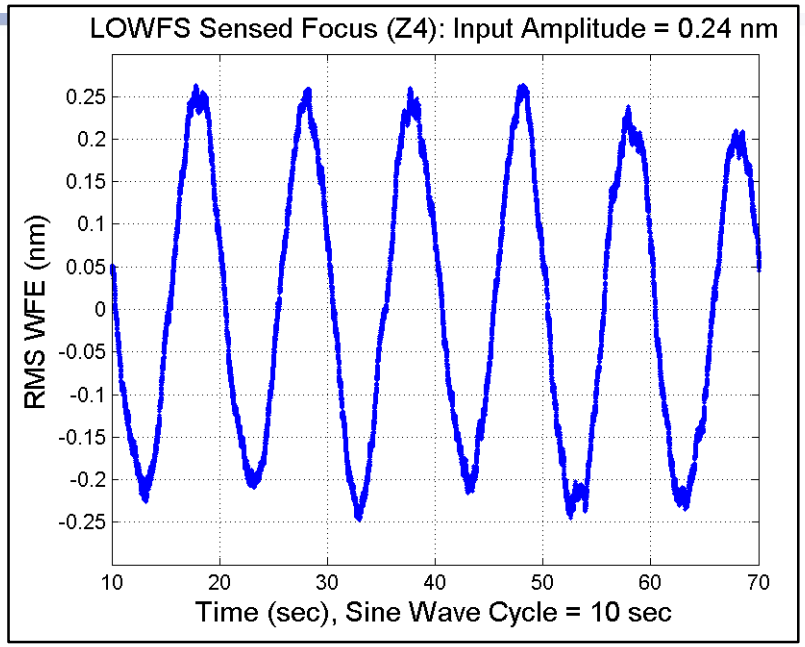


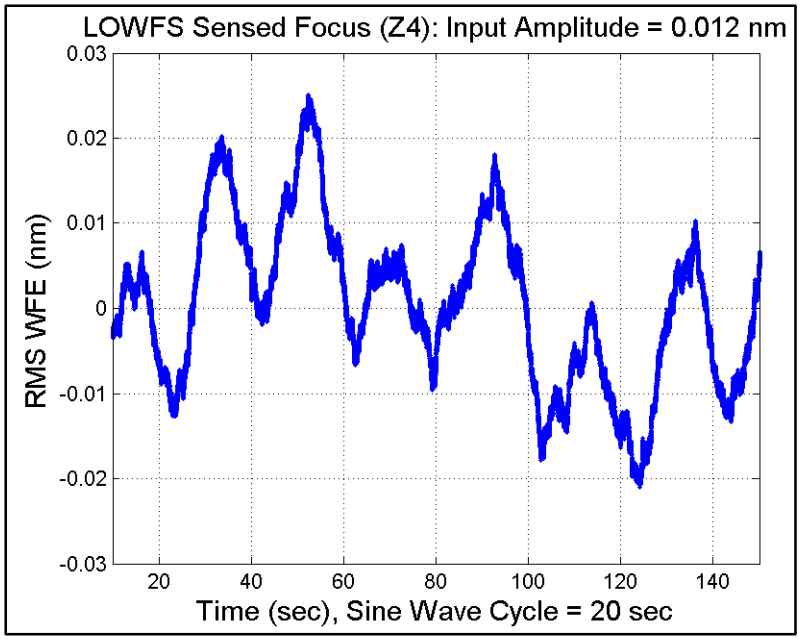


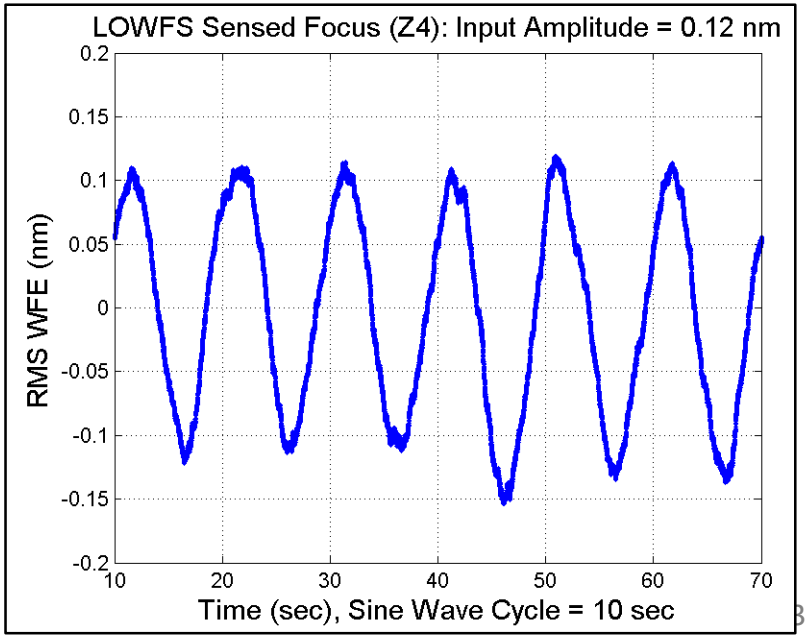
LOWFS measurements match independently calibrated OTA simulator

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)!**

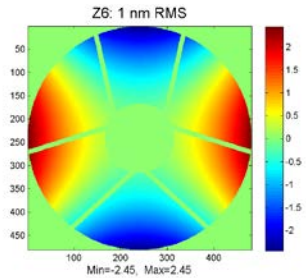


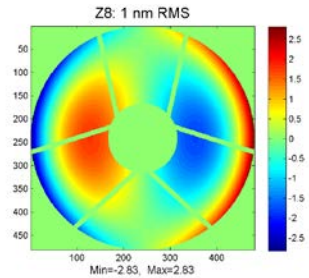


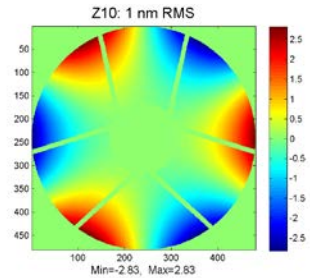


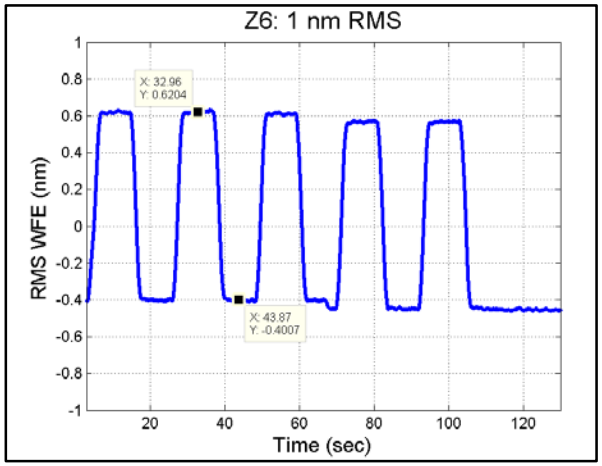
ZWFS Sensing: Other Low Order Modes

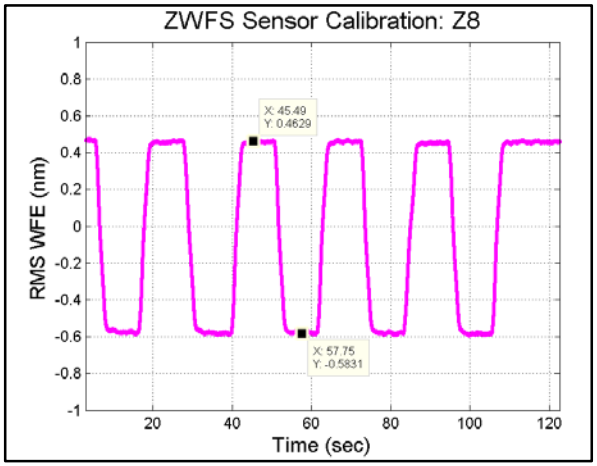
- Use DM1 on the testbed to create various low order modes on top of a dark hole HLC DM reference map
- WFE mode is modulated in a square wave pattern between a +1 nm rms aberration and reference with period ~20 sec.
- LOWFS signal smoothed (1 sec averaging) to reduce the sensor noise and detrended to remove the testbed drift
- Some cross-talk (10 – 30% depending on the mode) present due to testbed wavefront in dark hole condition instead of flat WF.

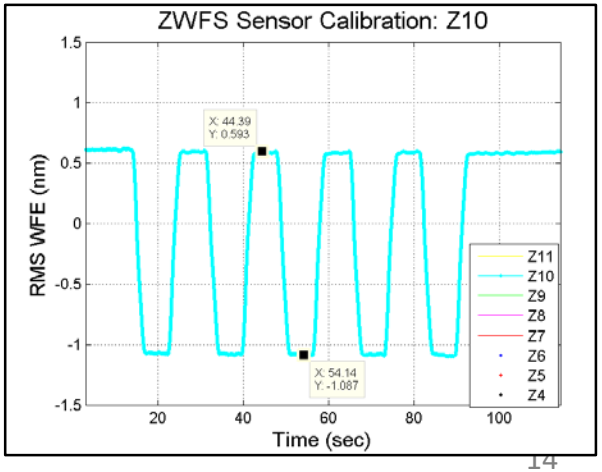




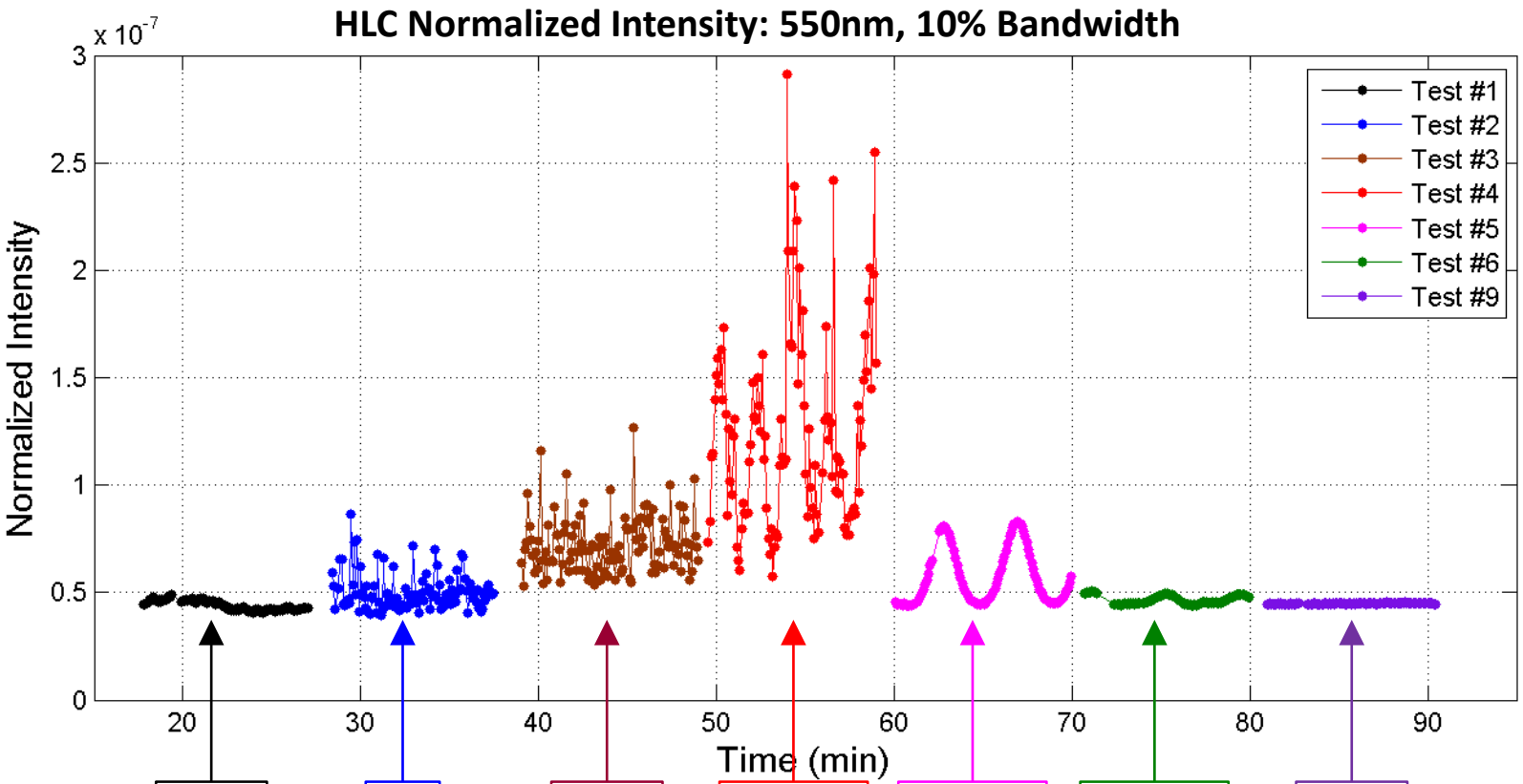








HLC LOWFS/C Dynamic Test



Open Loops: Lab Environment

Open Loops: LoS ACS Drift

Open Loops: LoS ACS Drift + RWA Jitter (600rpm)

Open Loops: LoS ACS Drift + RWA Jitter + Focus Since Wave Disturbance

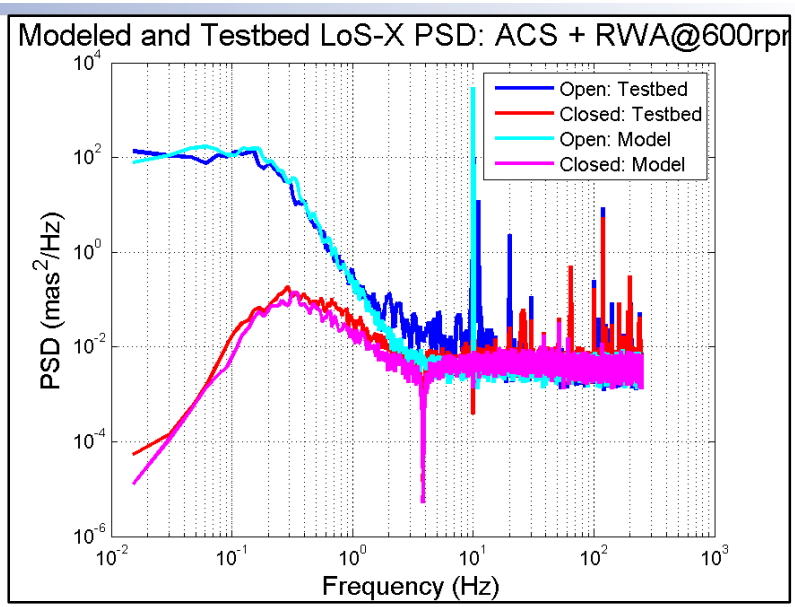
Close FSM FB&FF Loops: LoS ACS Drift + RWA Jitter + Focus Sine Wave

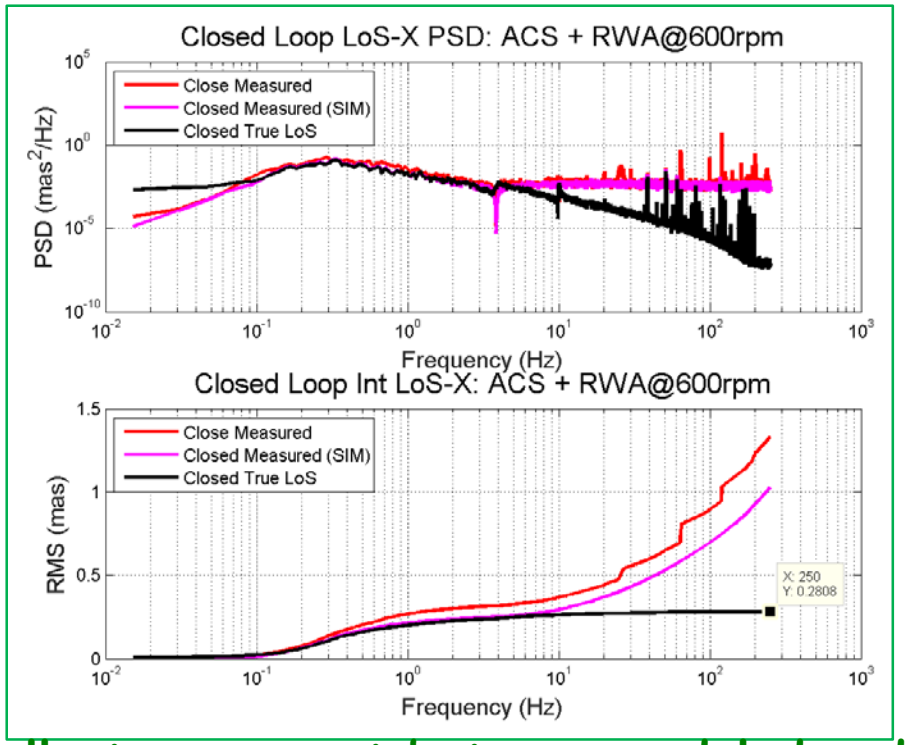
Close FSM & DM Loops: LoS ACS Drift + RWA Jitter + Focus Sine Wave

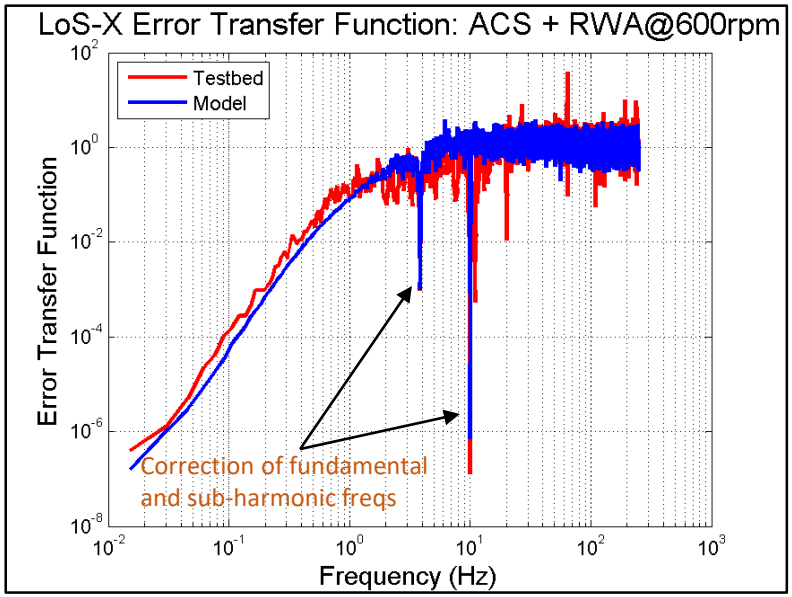
Close FSM-FB & DM Loops: Lab Environment

HLC LOWFS LoS Correction: Data vs. Model

- **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



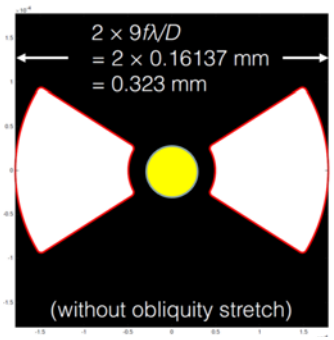


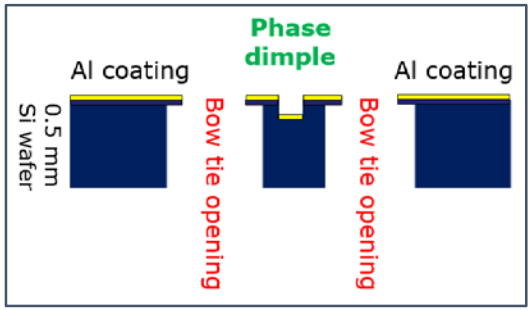


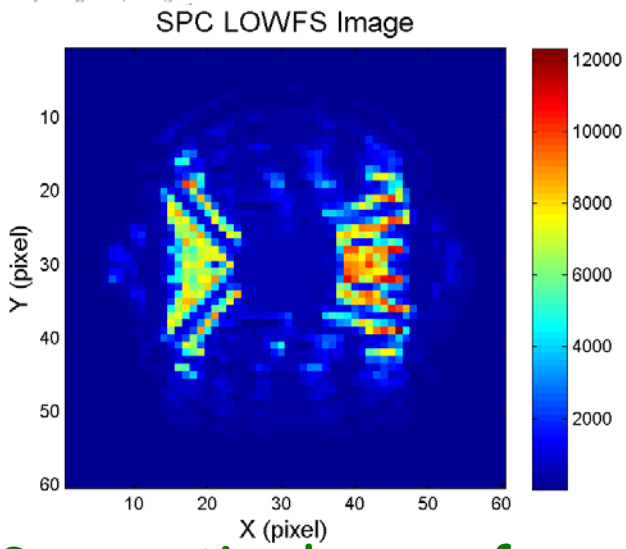
Excellent agreement between modeled and measured LoS loop performance

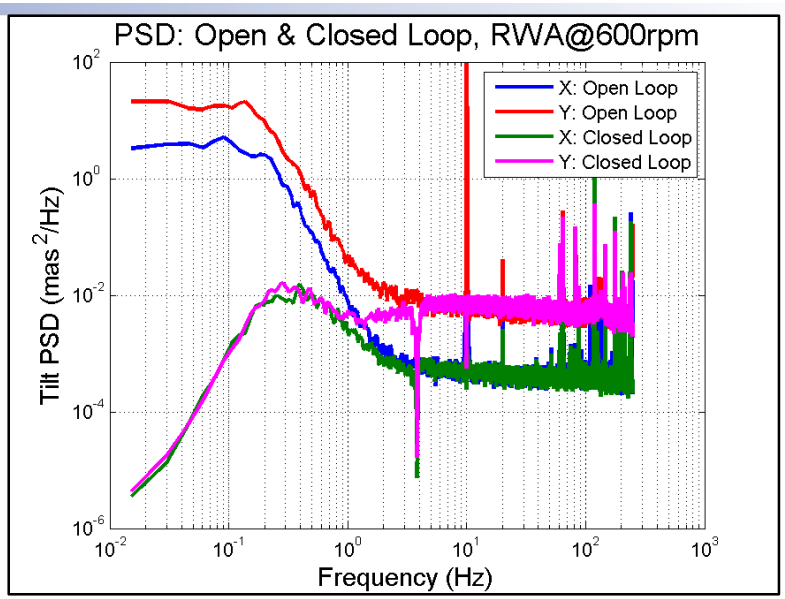
SPC LOWFS LoS Correction

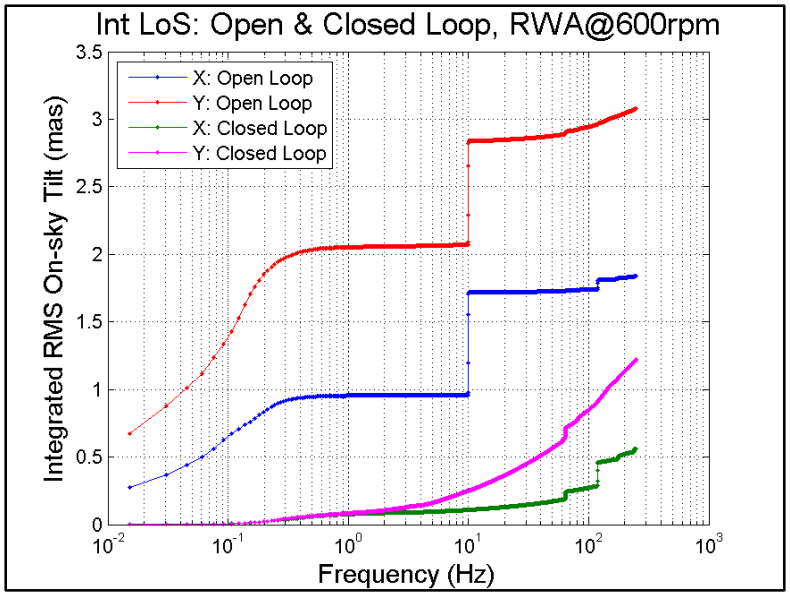
- **Zernike phase dimple built into new SPC "bowtie" occulting masks, fabricated at JPL's MDL**
- **Cycle 5 CBE LoS disturbances tested on the OMC testbed**
- **Residual error is dominated by the LOWFS sensor noise and testbed environment noise**
  - Asymmetric SPC PSF causes more sensor noise in Y







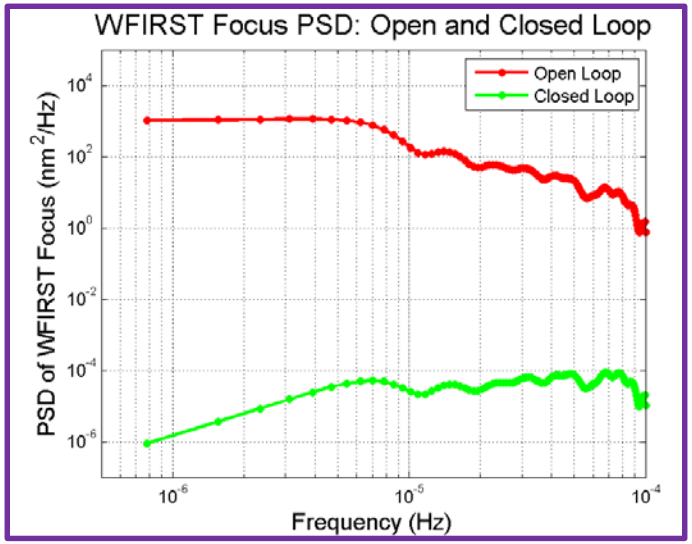


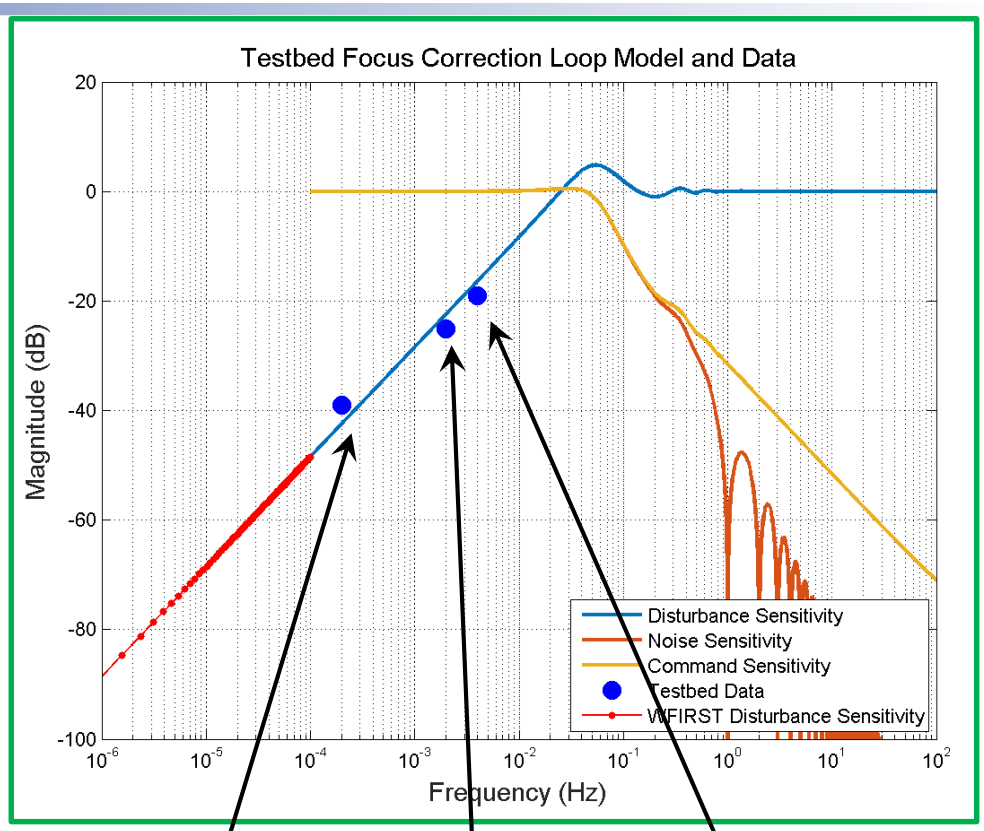


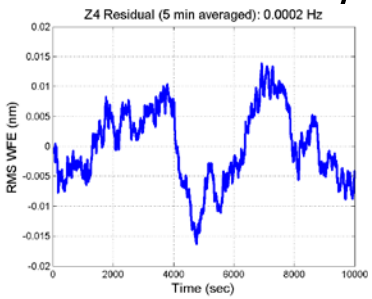
LoS correction loop performs well in both SPC and HLC modes

HLC LOWFS WFE Mode Correction: Focus

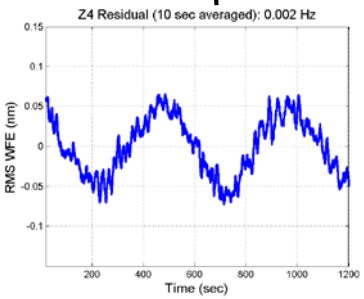
- Focus drift generated by OTA simulator
  - 2 nm P-V sinusoid, ~4x larger than flight
- DM #1 used to correct focus
- Testbed data matches control model prediction
- Projected WFIRST focus drift suppression is > 2 orders of magnitude
  - w/o LOWFS/C: Z4 drift ~ 0.5 nm (P-V)
    - Projected $\Delta C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



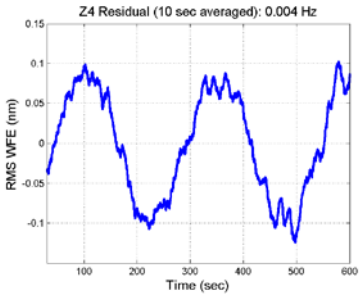




Residual Z4: 0.0002 Hz



Residual Z4: 0.002 Hz



Residual Z4: 0.004 Hz

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 and low order mode to the level of 12 pm rms

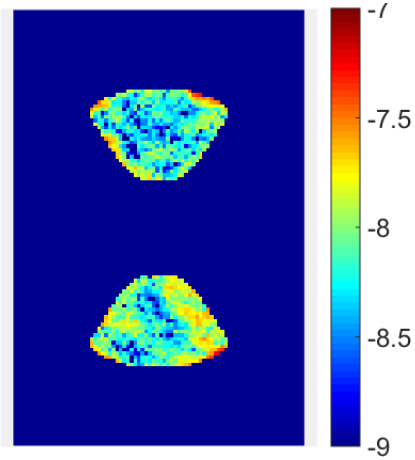
- LOWFS/C can maintain CGI contrast stability in presence of WFIRST LoS and low order WFE disturbances
  - Three modes (Z2, Z3, Z4) are the dominant disturbances for WFIRST
  - Correction greatly improves OMC contrast stability

- 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

Backup Slides

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)**

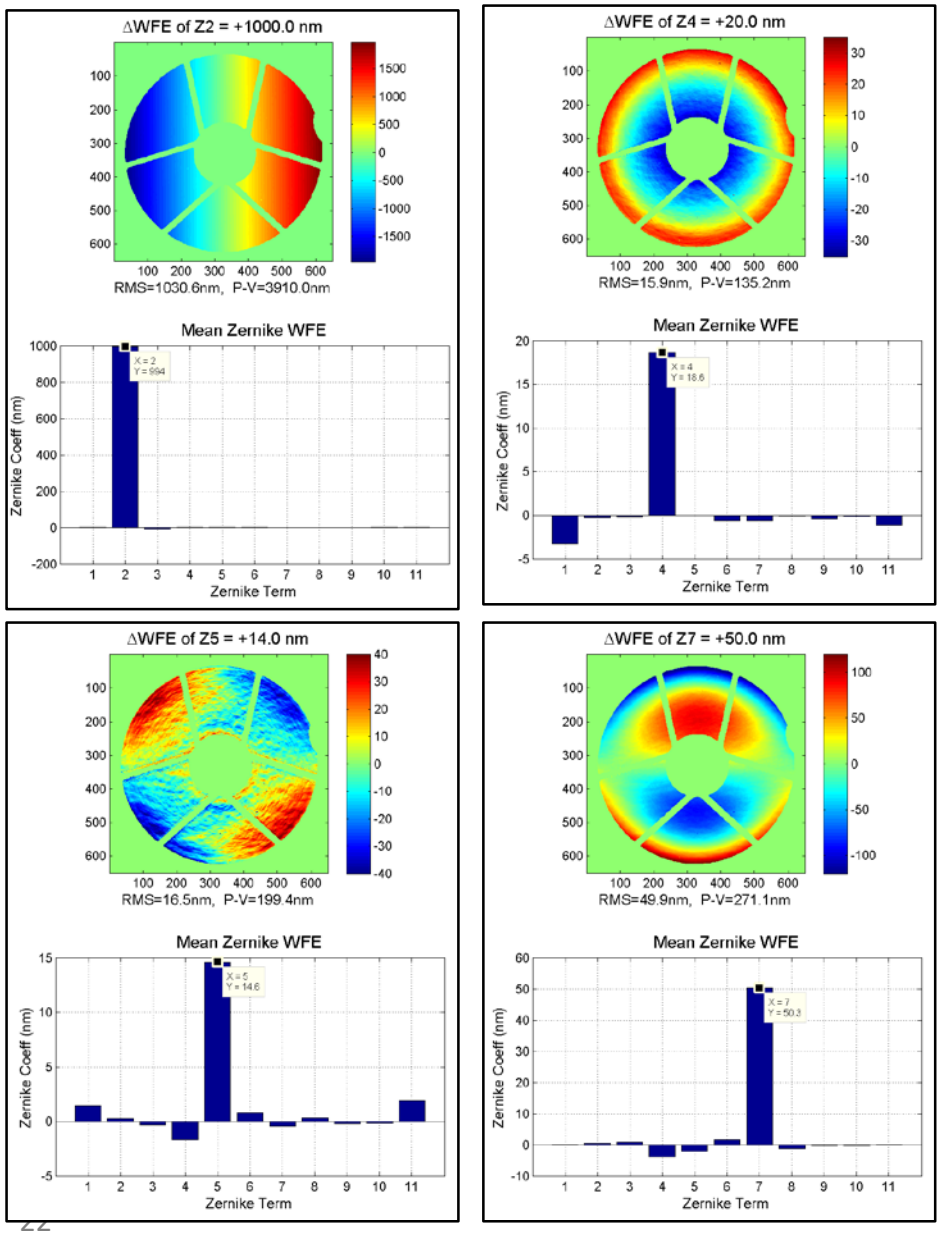
* HLC nulling run in progress after a recent H/W change; reached 1.0×10^{-8} 3-8.8 λ/D

** conservative extrapolation used

Calibration of OTA Simulator

- **OTA Simulator is used to generate WF aberrations and verify ZWFS performance**
- **Low order WFE modes are generated by small rigid body motion of powered optics using PZTs**
  - LoS tilts (dynamic): Z2 and Z3
  - Low order WFE: Z4 (focus), Z5 & Z6 (astigmatism), Z7 & Z8 (coma), Z11 (spherical)
- **Zygo in-air calibrations (double pass)**
  - Influence function of each PZT actuator.
  - Pure WFE modes Zygo measurement (double pass)
    - $\Delta OPD = Aberrated_{OPD} - Nominal_{OPD}$

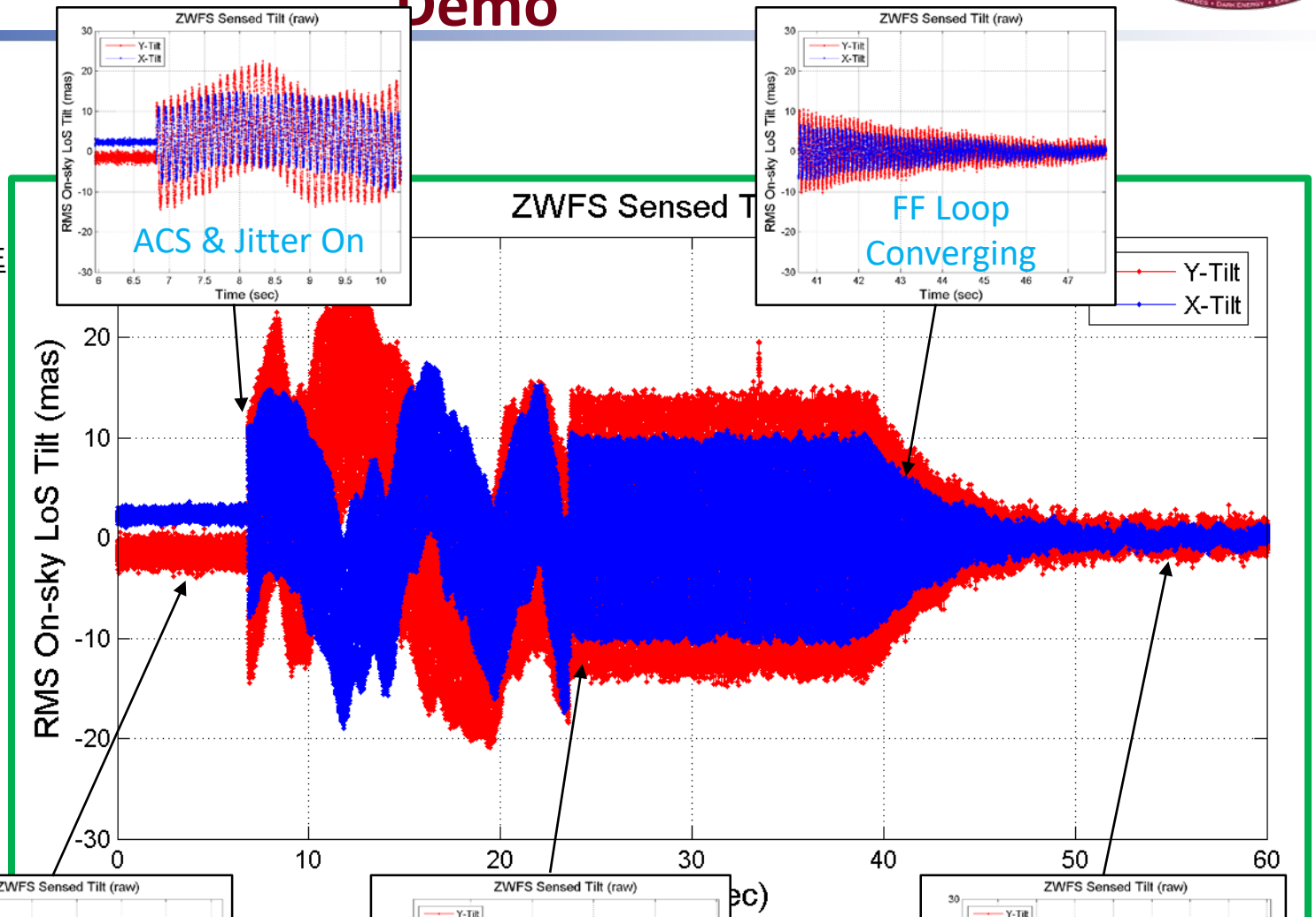
OTA simulator calibrations are used to generate sub-nanometer (rms) WF errors expected on orbit

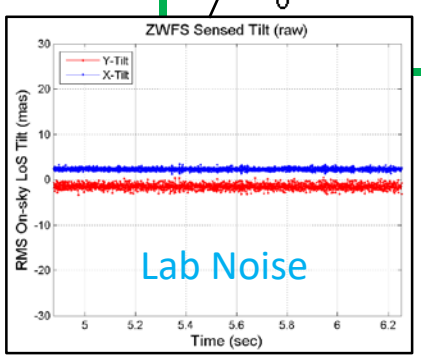


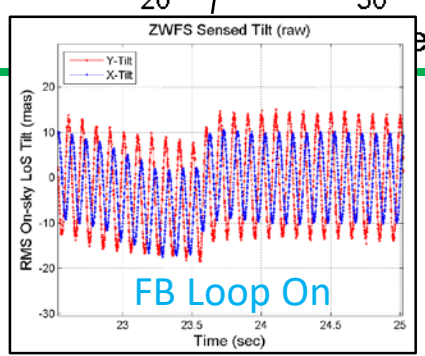
LOWFS/C LoS Feedback and Feedforward Loops Demo

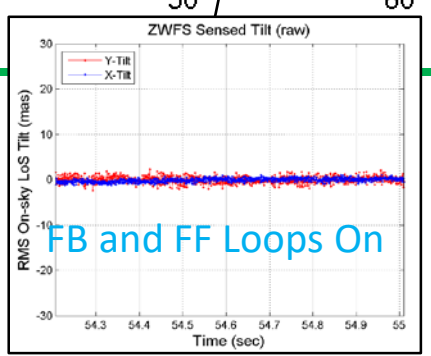
Jet Propulsion Laboratory
California Institute of Technology

- Disturbance: Cycle 5 CBE
- ACS LoS drift
- LoS jitter @ RW of 10 rev/sec (worst case)
- Small plot shows the zoomed in region





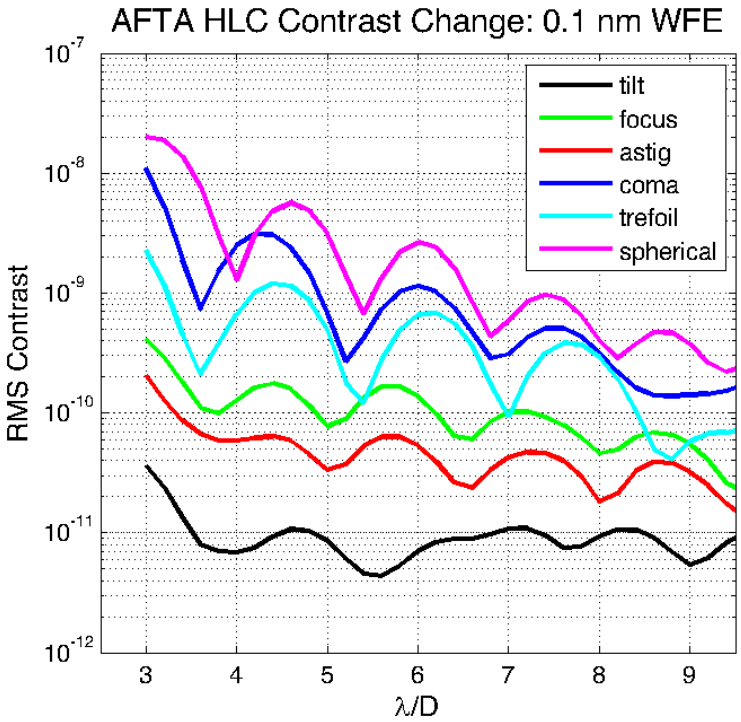


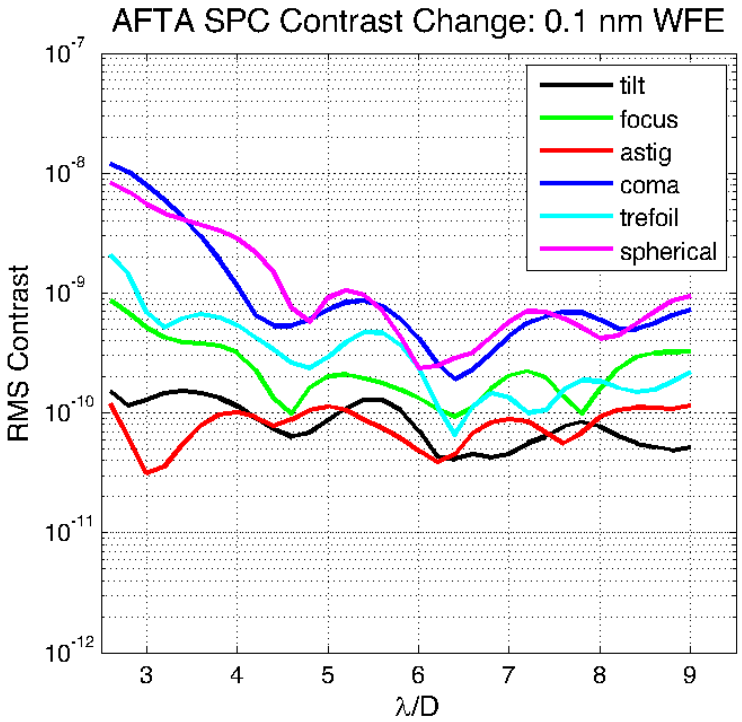


OMC Aberration Sensitivities

HLC and SPC WFE sensitivities modeled by J. Krist

- Compared to 2013 ACWG downselect, HLC sensitivities are lower, SPC sensitivities higher (performance trade-off with the addition of Lyot stop)
- Sensitivity highest to spherical and coma





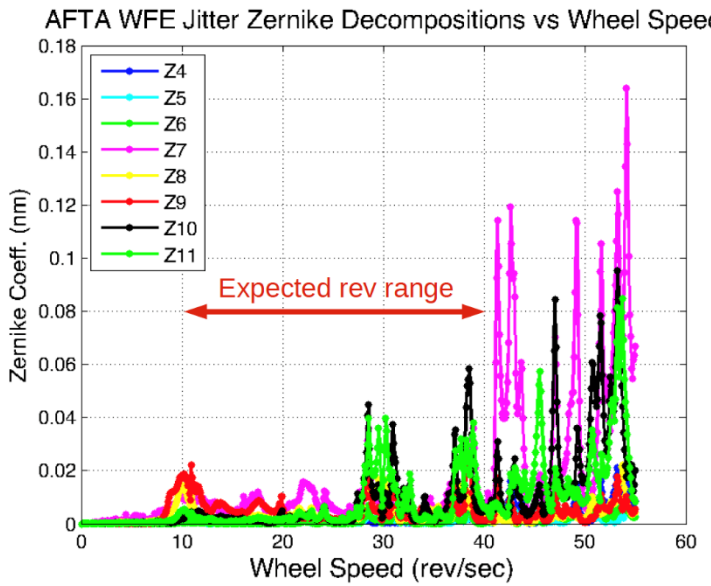
Impact of Pointing Jitter on OMC Science

- Number of known RV planets detectable in <1 day by HLC and SPC as a function of jitter and post-processing gain [W. Traub et. al., JATIS, submitted]
- Residual jitter of 1.6 mas rms per axis allows OMC to produce compelling science; selected as the requirement
- Residual jitter of 0.4 mas rms per axis selected as the goal

RMS jitter (mas)	post-processing factor (fpp)	# RV planets detected by HLC in <1 day each	# RV planets detected by SPC in <1 day each
1.6	10	13	11
0.8	10	14	13
0.4	10	14	14
1.6	30	14	15
0.8	30	15	15
0.4	30	15	15

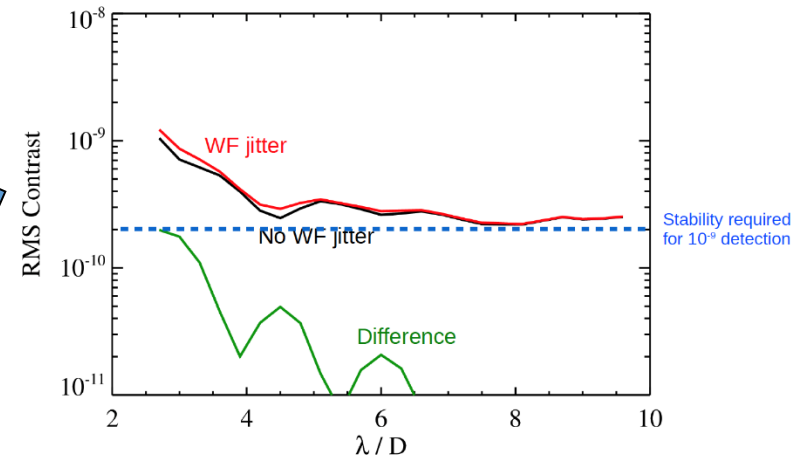
WFE Jitter and Impact on Performance

- **Expected RWA operating range: 10 - 40 Hz over 18 hours, with MUFs.**
- **Impact on OMC modeled by J. Krist**



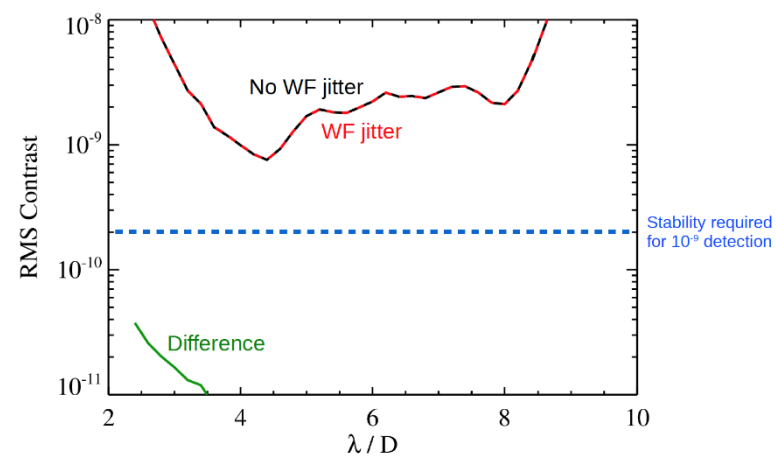
HLC with/without WF Jitter

523 – 578 nm, no pointing jitter, HLC 20140623-139



SPC with/without WF Jitter

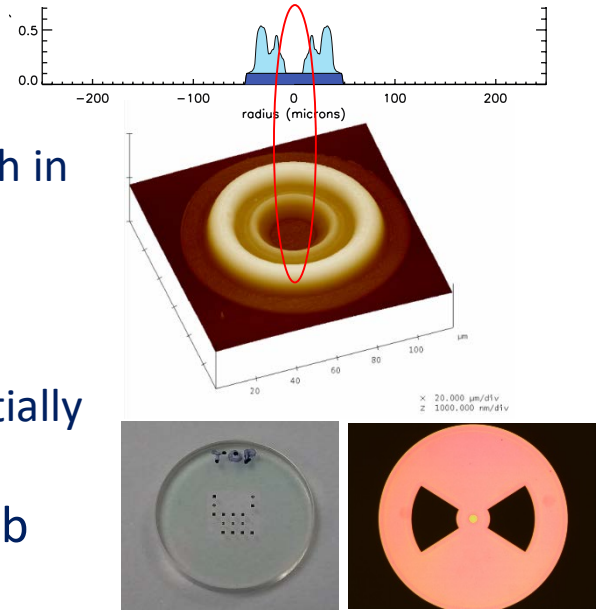
728 – 872 nm, no pointing jitter, SPC 20140902-1

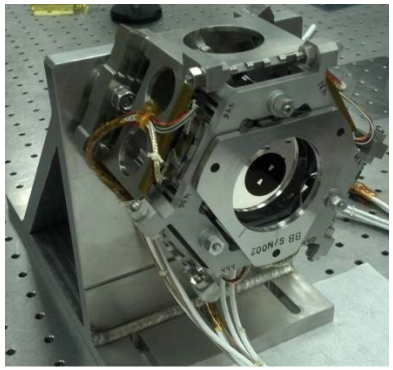


- WFE jitter is not significant error budget contributor
  - except HLC @ 3λ/D
- WFE jitter sensing and correction not baselined for OMC

Key LOWFS/C Hardware

- **Coronagraph/LOWFS focal plane masks**
  - HLC/LOWFS occulter
    - Harder case: occulter center used for coronagraph in transmission, LOWFS in reflections. Performance validated: nulling (MS 5) and LOWFS (MS 6)
  - SPC/LOWFS occulter
    - Easier case: coronagraph and LOWFS regions spatially separated on occulter
  - Both masks fabricated at JPL's MicroDevices Lab
- **LOWFS camera. Used CCD39 for initial demo**
  - SciMeasure camera electronics implementation does not meet its 7.5e- read noise spec at 1kHz
  - Options that meet spec exist with no new technology (engineering only)
- **Fast Steering Mirror. High TRL unit built for SIM**
  - Performance extensively characterized for WFIRST

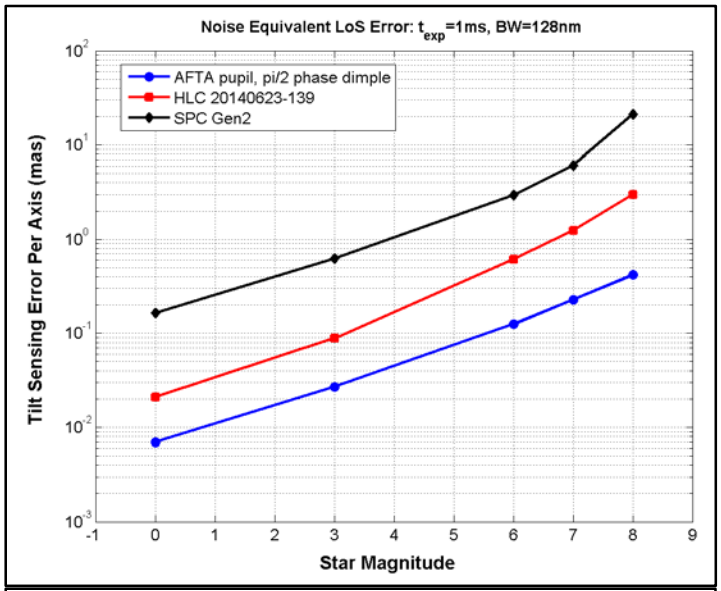


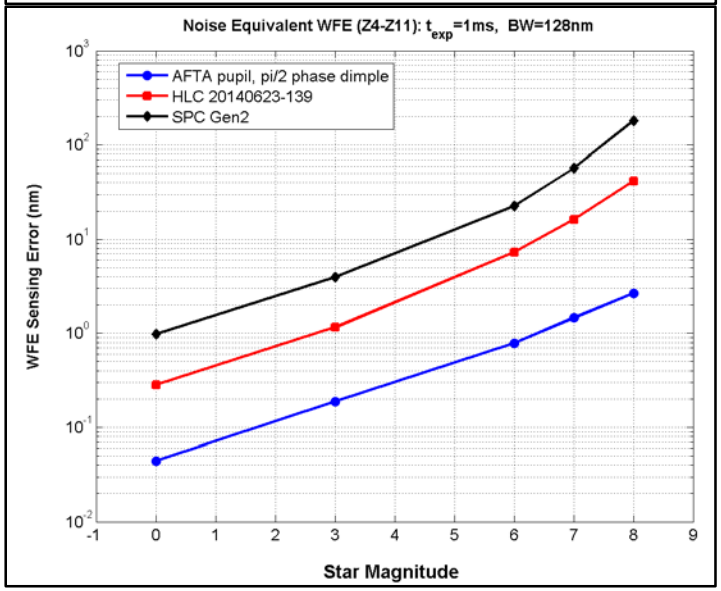


High TRL for key LOWFS hardware

ZWFS Modeling and Performance Analysis

ZWFS Noise Equivalent Sensing Error

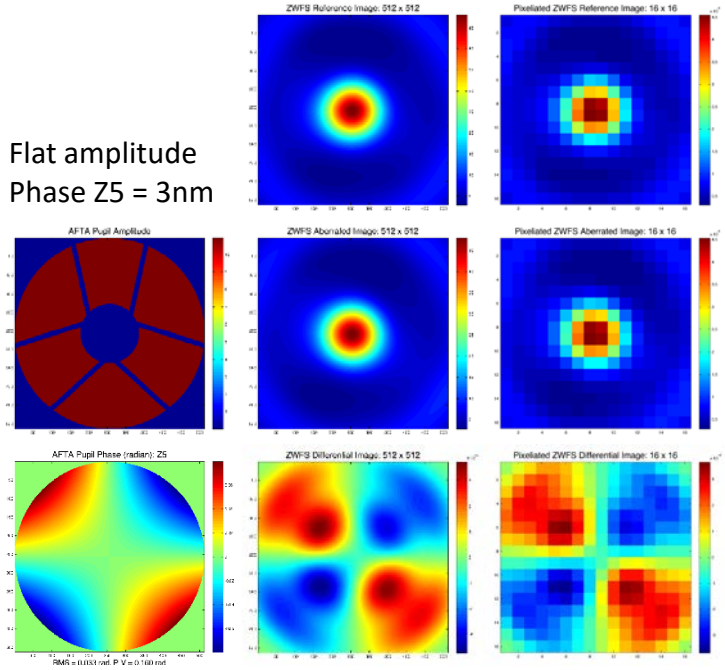




- **Diffraction models of ZWFS for HLC and SPC used to analyze the ZWFS performance**
- **ZWFS noise equivalent errors (LoS and WFE)**
  - PSF difference caused by diffraction (SPC) or DMs (HLC) increases the ZWFS sensing error
  - Plots on the left is ZWFS @ 1 msec exposure (CCD readout at 1 KHz)
    - For slow varying WFE, image averaging will lower the equivalent M_V

Sample Images of HLC/ZWFS

Flat amplitude
Phase Z5 = 3nm



WFIRST CGI LOWFS performance has been extensively modeled