WFIRST Coronagraph Technology Development Testbeds: Status and Recent Testbed Results

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Note: the materials in this packages will be used to compose a poster for 231st AAS

Outline

- **WFIRST coronagraph technology development testbeds**
  - Occulting Mask Coronagraph (OMC) dynamic testbed
  - Shaped Pupil Coronagraph and Integral Field Spectrograph (SPC/IFS) testbed
- **WFIRST technology development milestones status**
- **Tech Testbed result highlights**
  - HLC and SPC coronagraph dynamic tests with LOWFS/C rejection of WFIRST like line-of-sight disturbances and wavefront drifts.
  - Demonstration of EFC control (dark hole digging) using 3 band filters instead of 5 bands to improve the EFC efficiency.
  - Demonstration of simultaneous EFC control (dark hole digging) and LOWFS/C with presence of WFIRST like disturbances for both HLC and SPC.
  - Improve HLC contrast jitter sensitivity using broadband tip-tilt EFC during dark hole creation.
  - Test of a high throughput asymmetric HLC mask.
  - Demonstration of EFC control using integral field spectrograph (PISCES) with 18% band on SPC/IFS testbed
  - Disk science shaped pupil mask coronagraph test
- **Conclusion and future work**

WFIRST CGI Tech Testbeds

- **Various testbeds have been built for WFIRST Coronagraph Instrument (CGI) technology development**
- **Theses testbeds address the key technical challenges for WFIRST CGI**
  - **Hybrid Lyot Coronagraph Testbed**: a static testbed to demonstrate HLC coronagraph contrast (<1e-8 contrast, 10% bandwidth) with WFIRST aperture.
  - **Shaped Pupil Coronagraph Testbed:** a static testbed to demonstrate SPC coronagraph contrast (<1e-8 contrast, 10% bandwidth) with WFIRST aperture.
  - **PIAACMC Testbed:** test the WFIRST backup coronagraph PIAACMC architecture.
  - **Low Order Wavefront Sensing and Control (LOWFS/C) Testbed**: demonstrate LOWFS sensor and line of sight control for WFIRST CGI as well as the OTA-Simulator to generate dynamic disturbances of line-of-sight and low order wavefront error
  - **Occulting Mask Coronagraph (OMC) Testbed**: combine coronagraph (HLC & SPC), OTA-Simulator, and LOWFS/C to demonstrate the coronagraph performance under the WFIRST like dynamic disturbances.
  - **SPC/IFS Testbed**: a static Shaped Pupil Coronagraph plus an integral field spectrograph (IFS) PISCES (Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies) to demonstrate IFS wavefront control for coronagraph
  - **Vacuum Surface Gauge (VSG)**: a high precision interferometer testbed to test, characterize, and calibrate the deformable mirrors (DM)
- **Early testbed activities greatly have reduced the technical gaps for WFIRST.**

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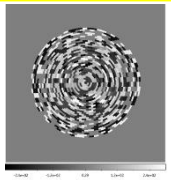
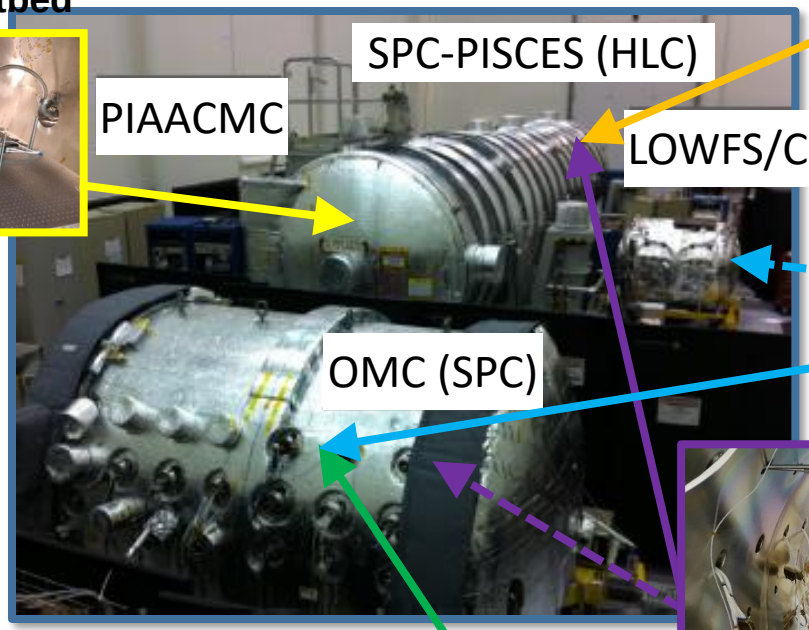
WFIRST Tech Testbeds in Pictures

PISCES

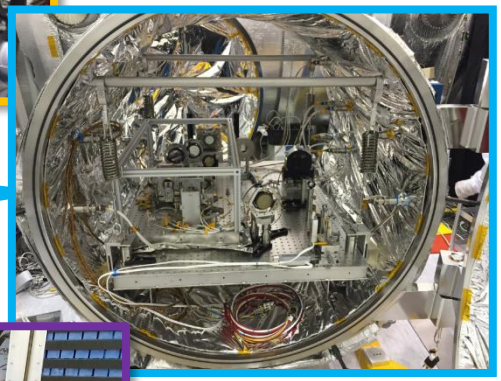
HCIT Testbeds

PIAACMC Testbed

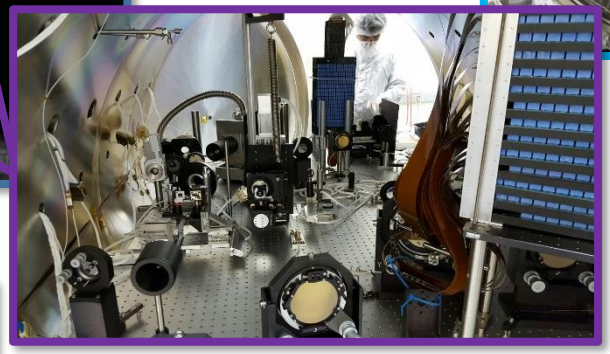




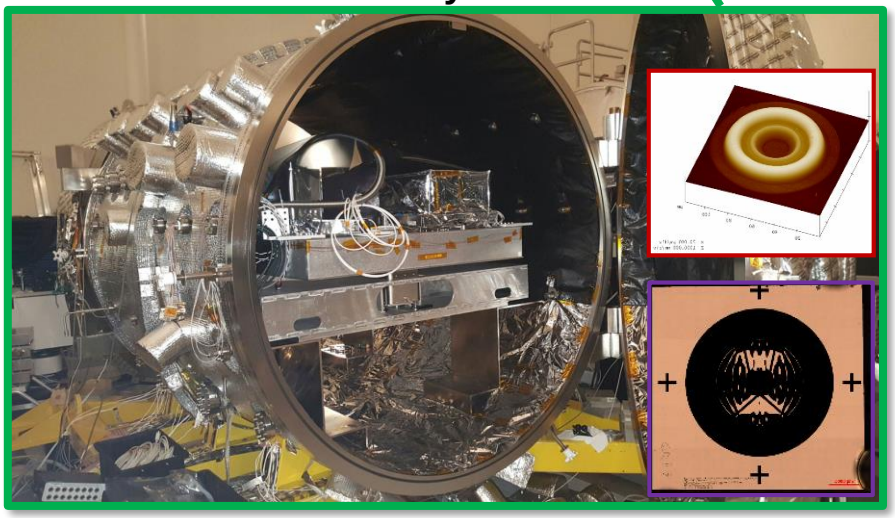
LOWFS/C Testbed



SPC Testbed

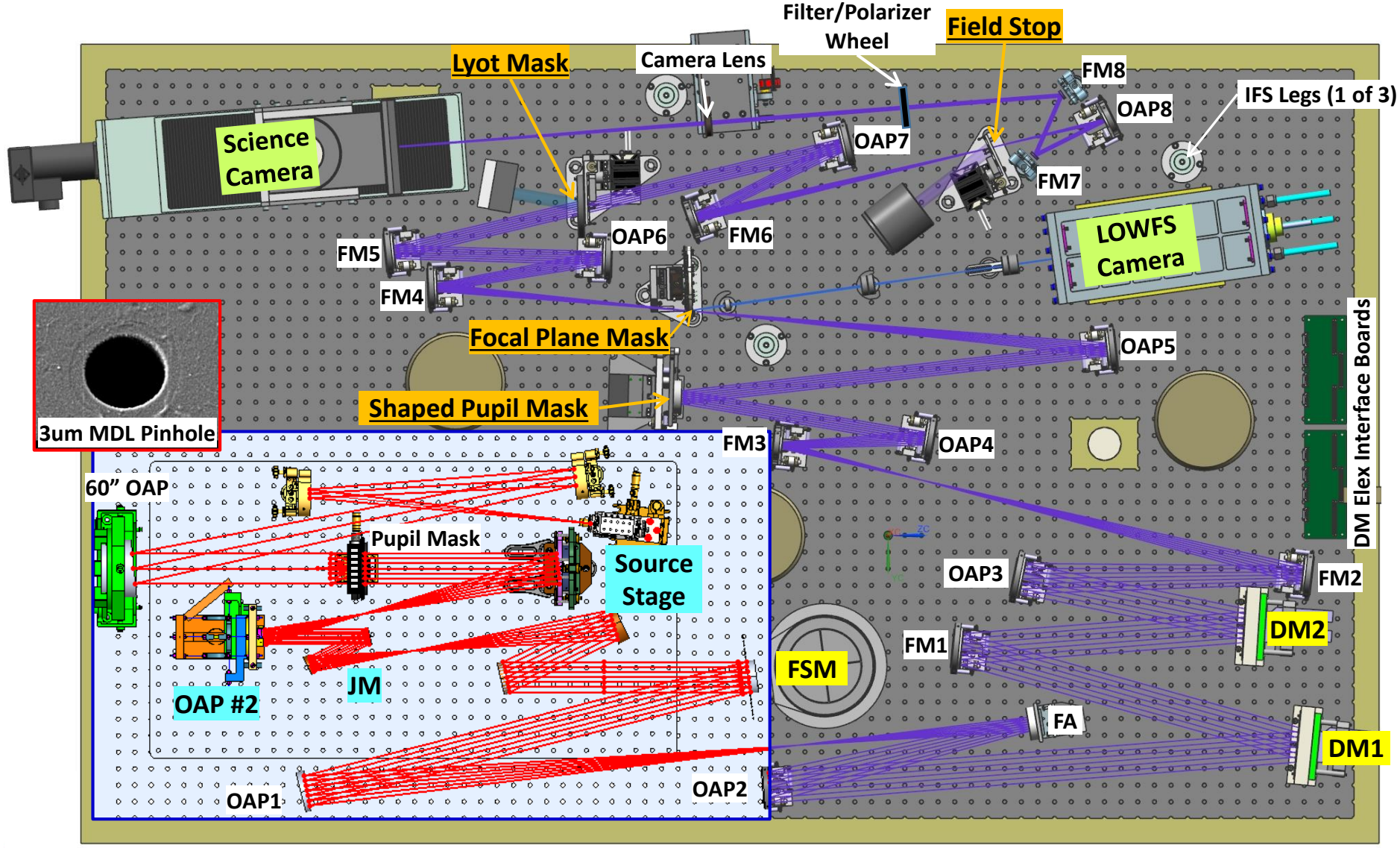


OMC Testbed for Coronagraph-LOWFS/C Dynamic Test



VSG for DM characterization

Occulting Mask Coronagraph (OMC) Dynamic Testbed



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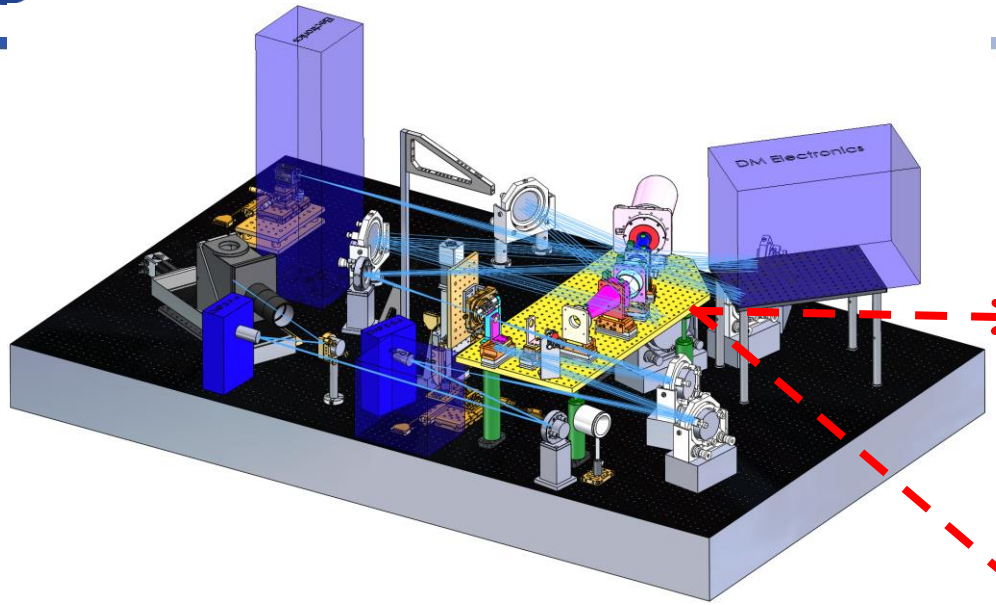
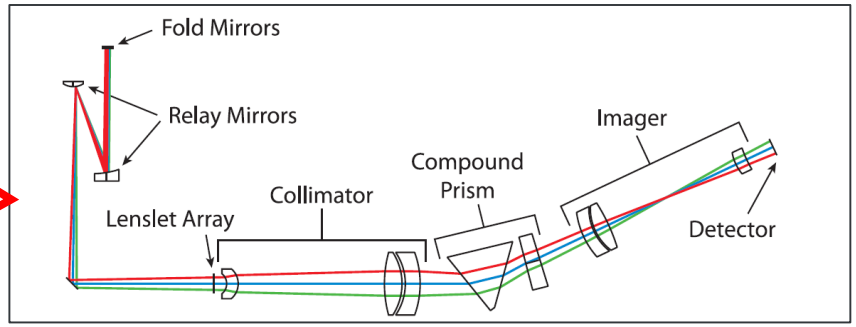
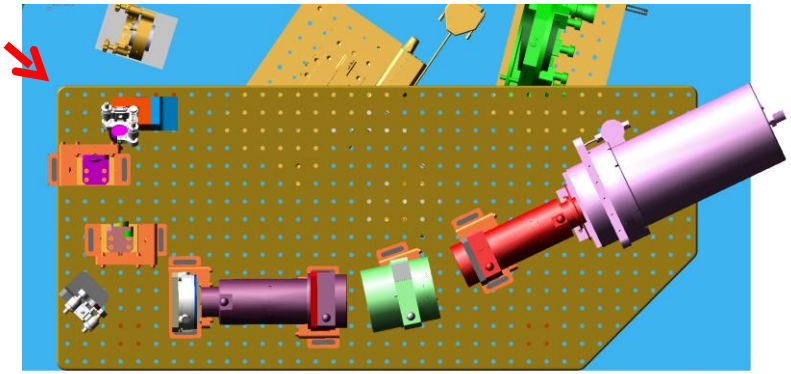
SPC / IFS (PISCES) Testbed



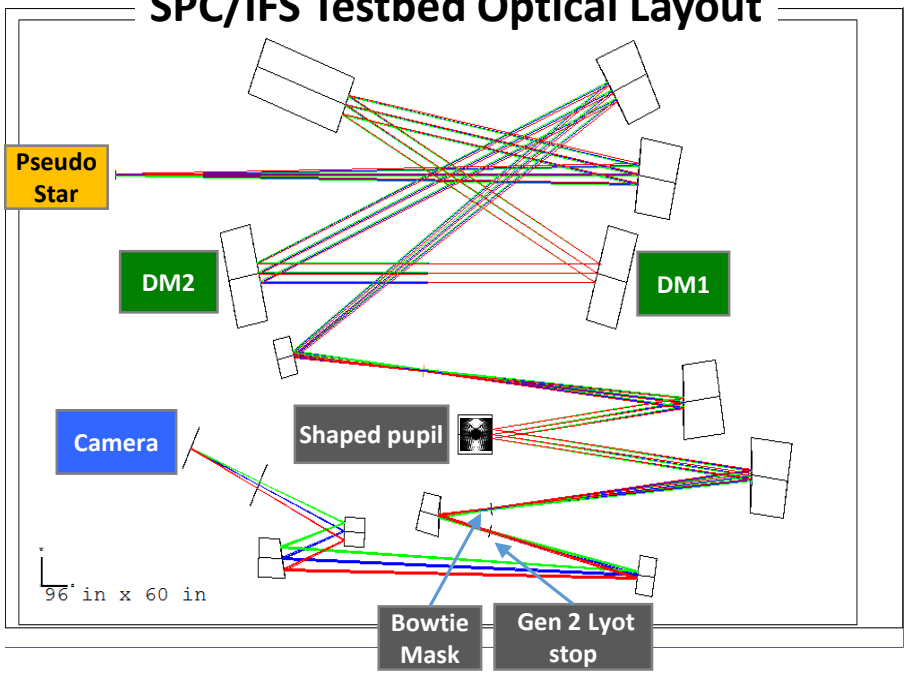
PISCES Optical Layout



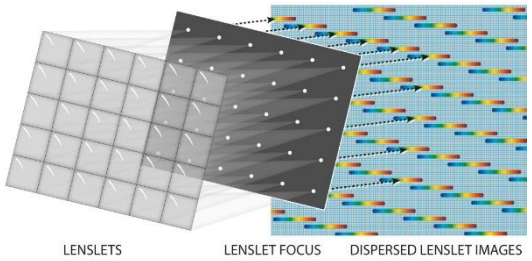
PISCES Sub-bench



SPC/IFS Testbed Optical Layout



PISCES Spectral Image



CGI Tech Testbeds Milestone CY'17

- **Key milestones for CY 17 concentrate on flight like configurations and operations**
- **Currently the progress is on track**

Milestones	Milestone Date	Status	Status Comments
PISCES commissioning done. Calibration and data pipeline in place	12/31/2016	**Done**	In HCIT2
Close out Milestone 9.	1/31/2017	**Done**	Review slides cleared
HLC wavefront control with <=3 bandpass filters (# engineering filters for flight).	3/31/2017	**Done**	In HCIT1, 3 bandpass done and has reached ~4e-9
Demonstrate simultaneous EFC and LOWFS/C operation.	5/31/2017	**Done**	In HCIT1, HLC & SPC contrast converges, LOWFS/C follows EFC reference
SPC wavefront control using PISCES IFS. 18% band high contrast.	5/31/2017	**Done**	In HCIT2, 18% band contrast 1.09e-8
Demonstrate SPC disc science mask performance with the imager, 6.5-20 λ/D.	9/30/2017	**Done**	In HCIT2, achieved 10% contrast of 8e-9 over 6.3-19.5 λ/D
High Efficiency HLC Mask Test	11/17/2017	**Done**	In OMC (HCIT1) testbed

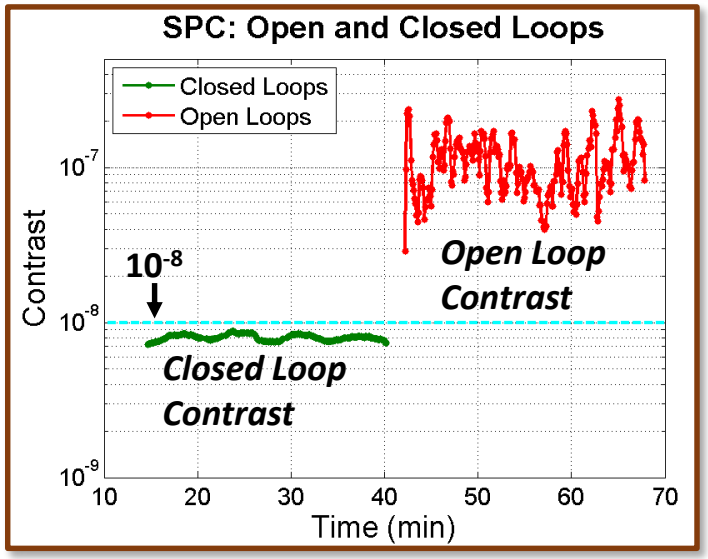
CGI Tech Testbeds Milestone CY'18

- **Key milestones for CY 18 concentrate on flight like configurations and operations**
- **Currently the progress is on track**

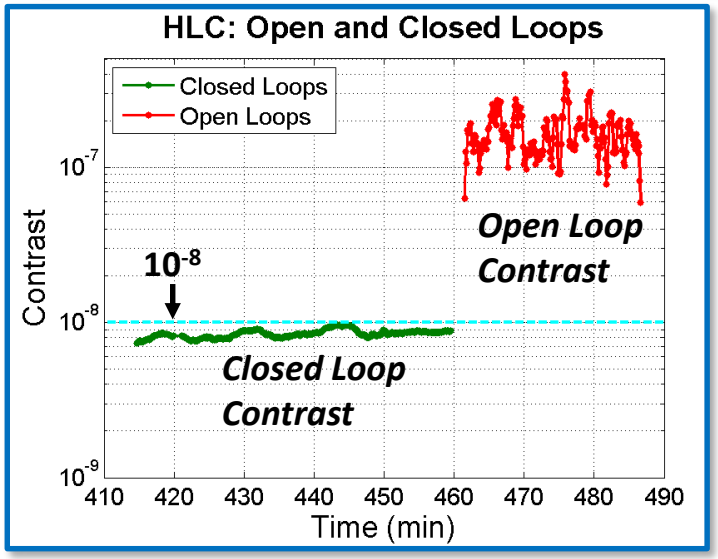
Milestones	Milestone Date	Status	Status Comments
SPC Disc Science Mask TRL5 Demo	2/28/2018	On-going	In SPC/IFS (HCIT2) testbed.
OMC Low Light (Low SNR) Tests	7/9/2018	On-going	In OMC (HCIT1) testbed. EFC on Mv=2 star and LOWFS/C on Mv=5 star
SPC/IFS 18% high contrast	2/9/2019		In OMC (HCIT1) testbed. Waiting for mask design to finalized.

Summary of Testbed Milestone 9 Results

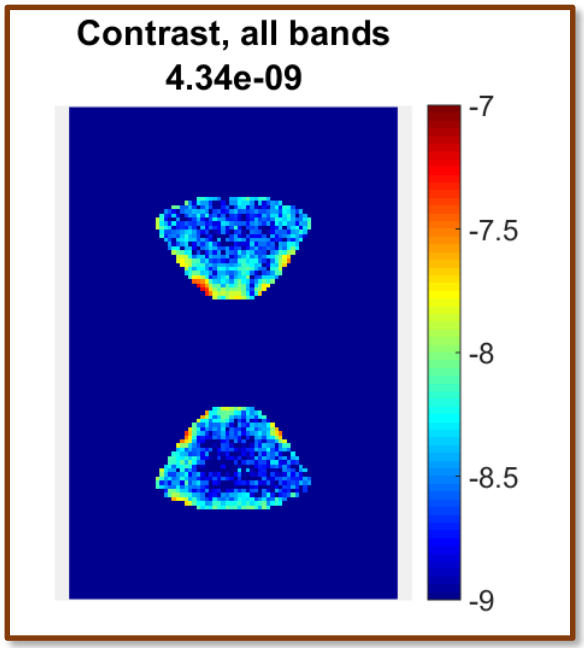
SPC Dynamic Test (10% at 550nm)



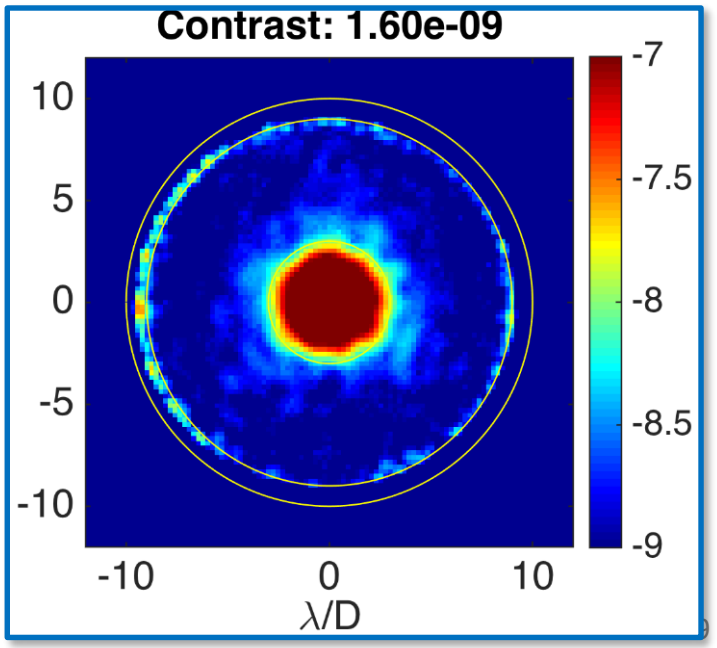
HLC Dynamic Test (10% at 550nm)



Best SPC Static Contrast (10% at 550nm)



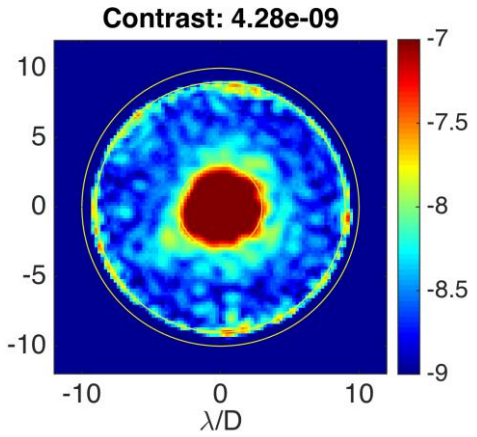
Best HLC Static Contrast (10% at 550nm)

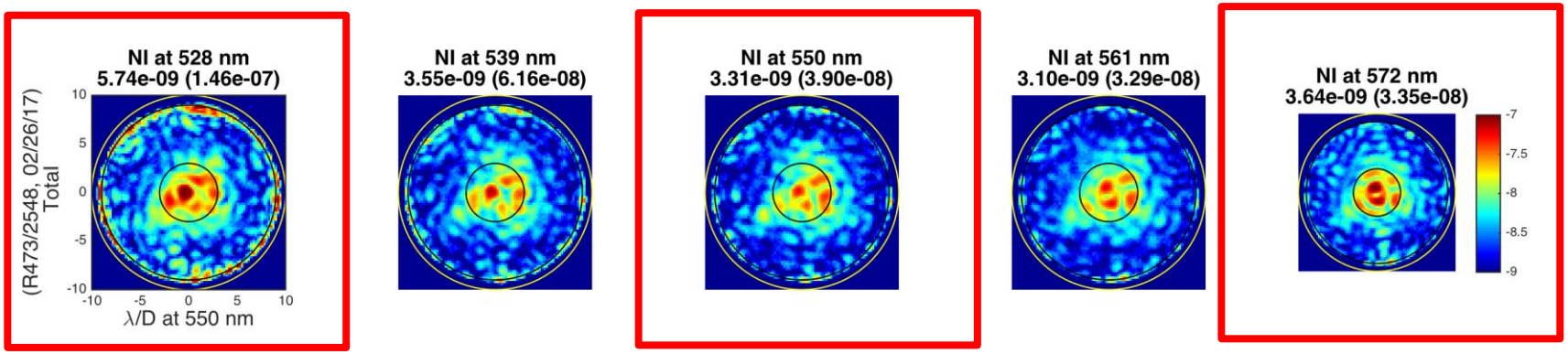


Increasing the WFC Efficiency by Using 3 Band EFC

- **Test Configuration**
  - Three bands (528 nm, 550 nm, 572 nm) nulling : Note that current OMC HLC occulter is designed at 550 nm.
  - 4 % bandwidth (22 nm) for each band : More aggressive configuration than current engineering filter bandwidth of 3.3 %.
  - Initial DM solution for EFC : DM flat. : It is the MOST aggressive initial condition we can think of. We like to confirm EFC works even with this extreme condition

10 % average at 550 nm ➔





Control bands Control bands Control bands

- **Results:**
  - Both the final 10 % contrast and its Zernike WFE sensitivity* are consistent with those of normal 5 band operation.
  - Bandwidth of the bands does NOT affect the end-result if the bandwidth is 2% ~ 4 %.*
  - Two-bands operation could NOT produce 5 band-consistent results.* *Not shown here.
  - **Three band EFC now become the standard operation on the testbed like flight**

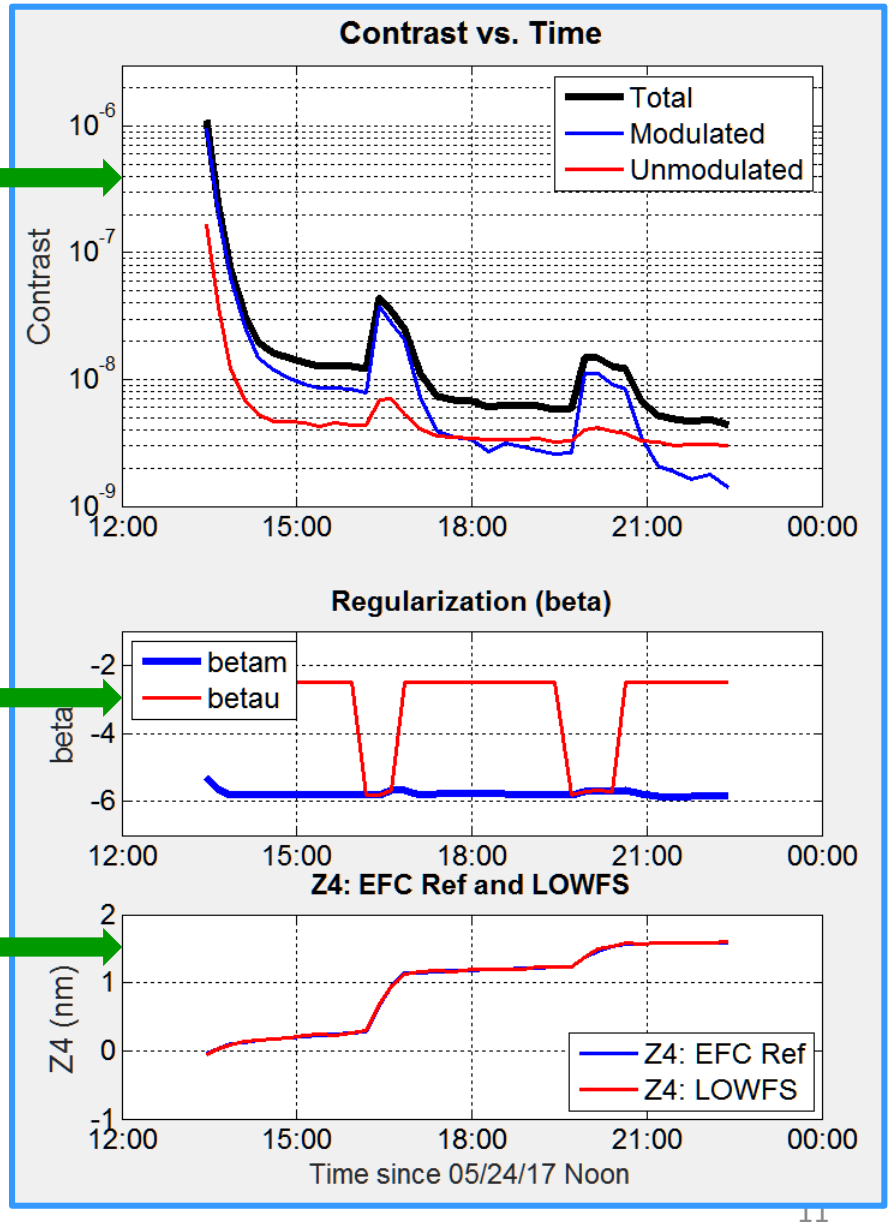
OMC Testbed: Simultaneous EFC & LOWFS/C

- **MS9 like disturbances using OMC Testbed's JM and Source Z actuator**
  - LoS drift = 8 mas; LoS jitter = 1 CBE at RWA = 600 rpm; Focus (Z4) drift = 1 nm sinusoidal with 60 minutes period
- **LOWFS/C loops using FSM and DM:**
  - LoS feedback loop (FSM)
  - LoS feed forward loop (FSM)
  - Low order WFE loop (DM #2)
    - LOWFS DM loop follows WFE target set by EFC
- **HLC EFC dark hole nulling operation:**
  - Use 3 band from filter wheel in front of SciCam simulating flight operation
  - Start with poor contrast to show case EFC convergence
  - EFC control set reference for LOWFS/C (LoS and low order WFE)
  - EFC control with varying regularizations
- **Test results have shown a successful simultaneous EFC and LOWFS/C operations:**
  - Contrast converges with simultaneous EFC & LOWFS controls
  - Coordinated controls between EFC and LOWFS/C loops, especially joint DM operations
  - LOWFS/C follows EFC set WFE target
  - LOWFS/C is helping EFC by correcting/reducing any low order WFE not specifically set by EFC

Contrast converges with simultaneous EFC & LOWFS/C

EFC varying regularization

LOWFS/C follows EFC set WFE ref

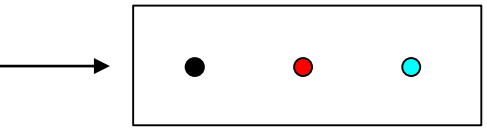


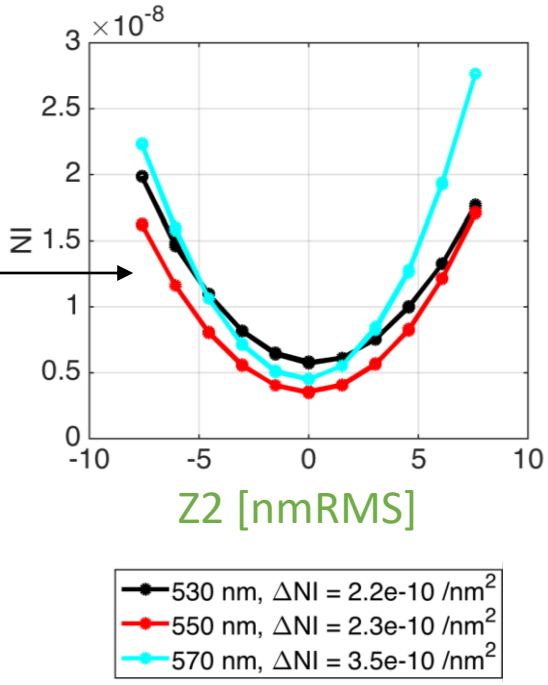
OMC Testbed: Improving HLC Jitter Sensitivity by Including Off-axis EFC

EFC control channels: color + off-axis

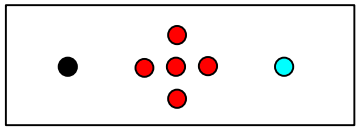
Dark hole tilt sensitivities: flatter curves -> better tilt sensitivity

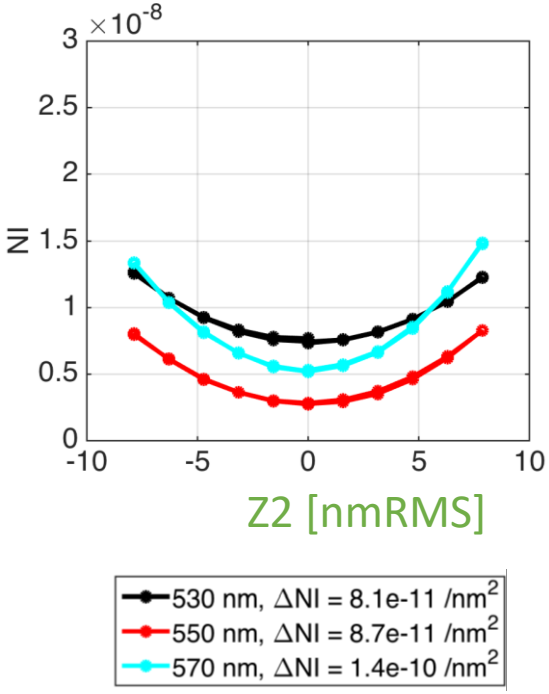
Broadband Control Only





Broadband + Off-Axis Control



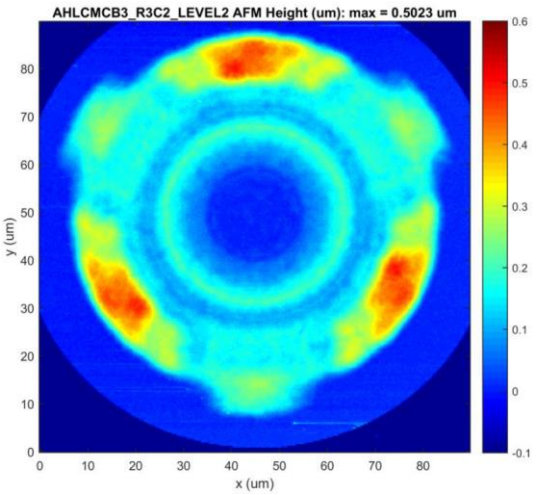


By including the off-axis control channels, the LoS sensitivity is improved by factor of 2 or higher (right plot, with tilt sensitivity in legend).

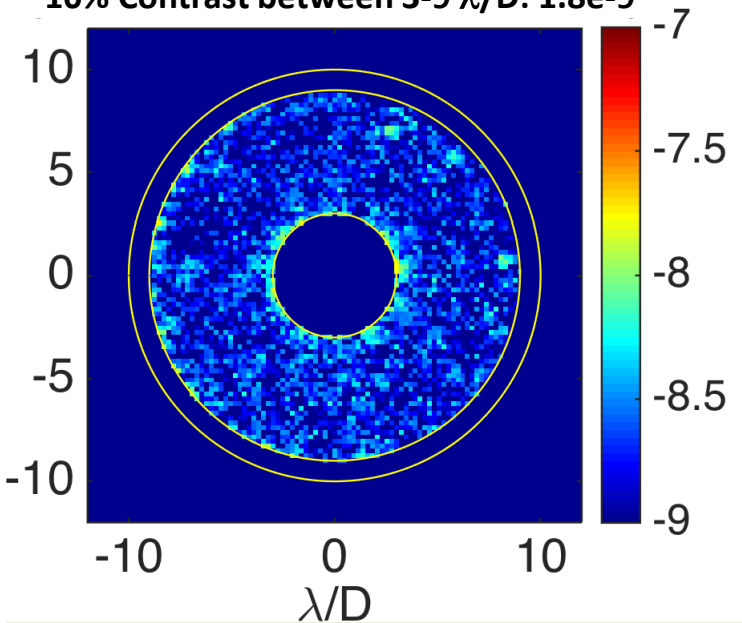
High Throughput Asymmetric HLC Mask on OMC Testbed

- New HLC design (AHLCMCB3-051717) is under test on OMC testbed since Sep. 2017. This new HLC is mostly designed for higher throughput with asymmetric dielectric profiles (right plot).
- Contrast: with this mask the HLC reaches 10% contrast level of 1.8e-9 between 3 – 9 l/D (lower plots).
- LOWFS: the LOWFS performance remains to be the same using this asymmetric mask.
- Coronagraph Throughput: The testbed throughput is measured at 4.4% at 550 nm, which is slightly less than design expected 5.9%. This compares to the previous design throughput (model-20150828-496) which was 3.5 % @ 550 nm in both measurement and model. The source of discrepancy is under investigation.
- New asymmetric HLC mask has better throughput

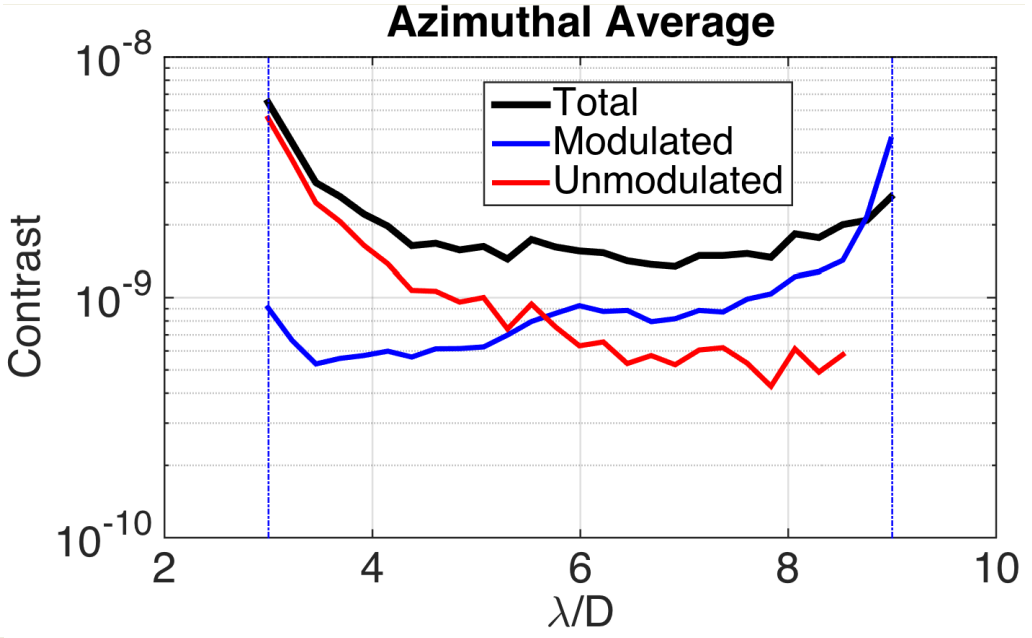
AFM Height Measurement



10% Contrast between 3-9 λ/D: 1.8e-9

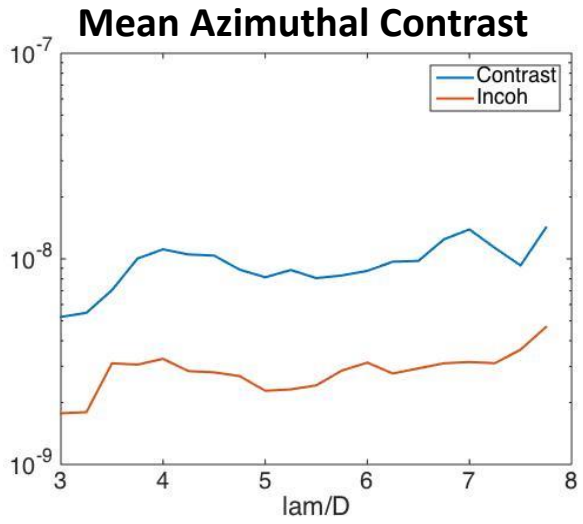


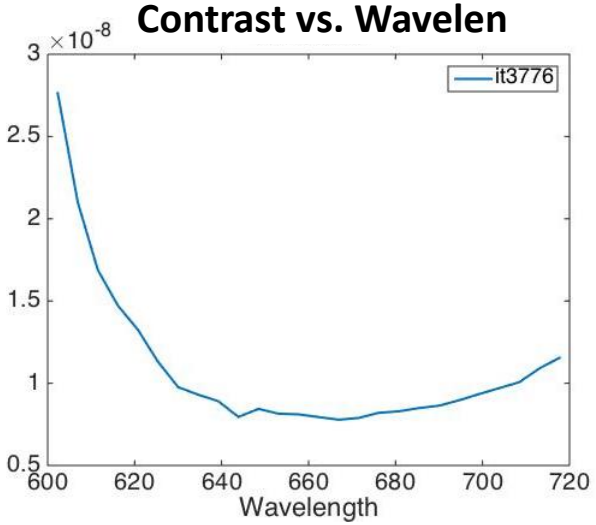
Azimuthal Average

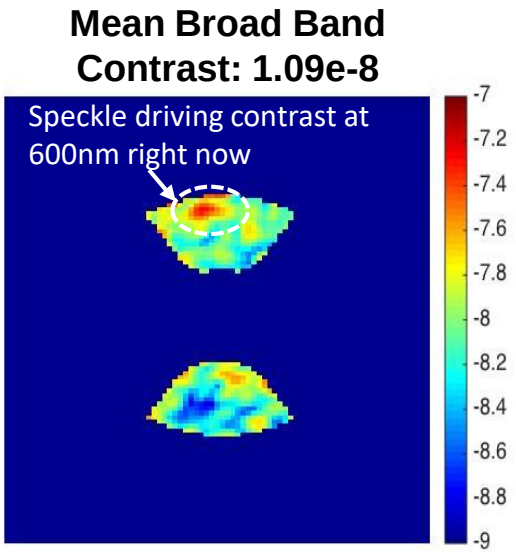


SPC/IFS Testbed: IFS Nulling in Broadband

- **SPC PISCES IFS 18% reached contrast 1.09×10-8 in an 18% band with IFS**
- **IFS data extraction creates 26 slices and 7 slices spread across the 18% band are used to do EFC control**
  - 18% Control at 660nm
  - Score: Two sides, 26 channels, 3-8 λ/D, at λ = 650 nm
  - Control: Two sides, 7 channels, 2.5-9.5 λ/D, at λ = 750 nm
- **GSFC PISCES team implemented second pipeline extraction scheme using the 2D fits ("lstsq") in place of 1D fits ("optext")**
  - Though in current test still uses "optext" the "lstsq" produces residual maps which will be useful for future performance analysis



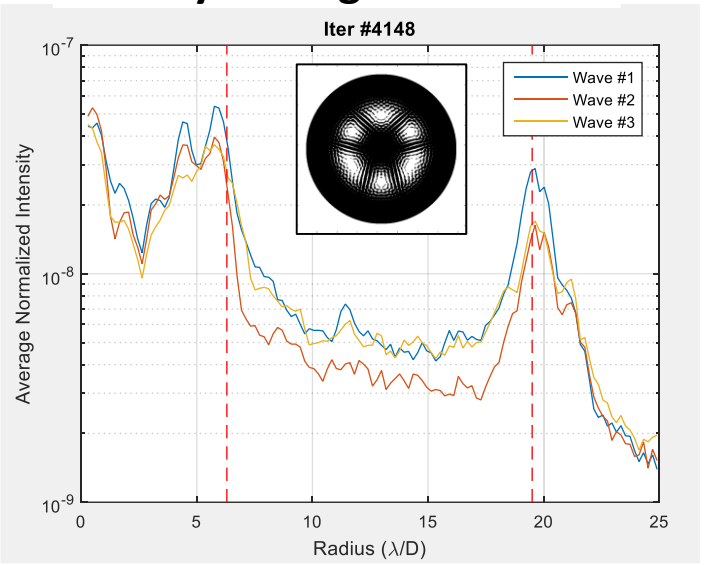




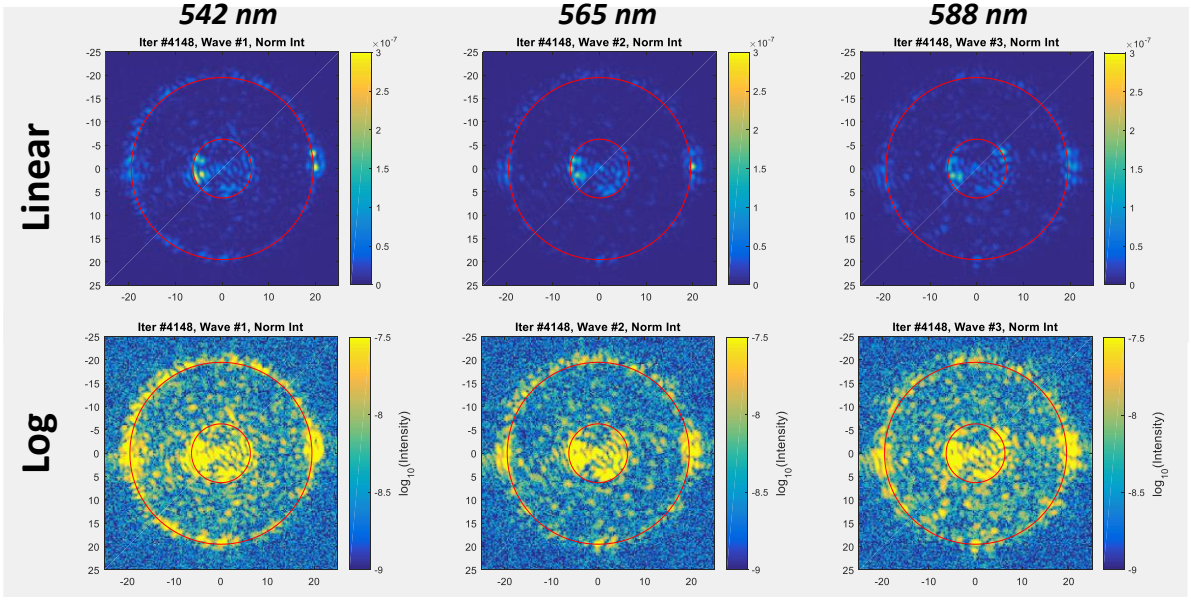
Disk Science Mask Test on SPC/IFS Testbed

- **Disk science mask (DSM) is one of the three coronagraph modes for WFIRST CGI.**
  - 360 degree dark hole extended up to 20 λ/D
  - Provides a powerful tool to study exozodiacal dust clouds associated with stellar debris disks to gain insight of the exoplanet formation and stellar disk dynamics.
- **DSM masks were fabricated by JPL's Micro Device Lab (MDL)**
  - A total of 9 shaped pupil mask samples of two different designs for disk science (1Kx1K and 2Kx2K pixels) were fabricated and characterized in June '17
  - 35mm x 35mm x 4mm silicon substrates with Al and black silicon binary features
- **Current best contrast from DSM: averaged 10% contrast evaluate between 6 – 19.5 l/D is *8e-9***

Radially Averaged NI Profile



SPC imager 3 bands normalized intensity: linear (top) and logarithmic (bottom) stretched



Disk Science Mask

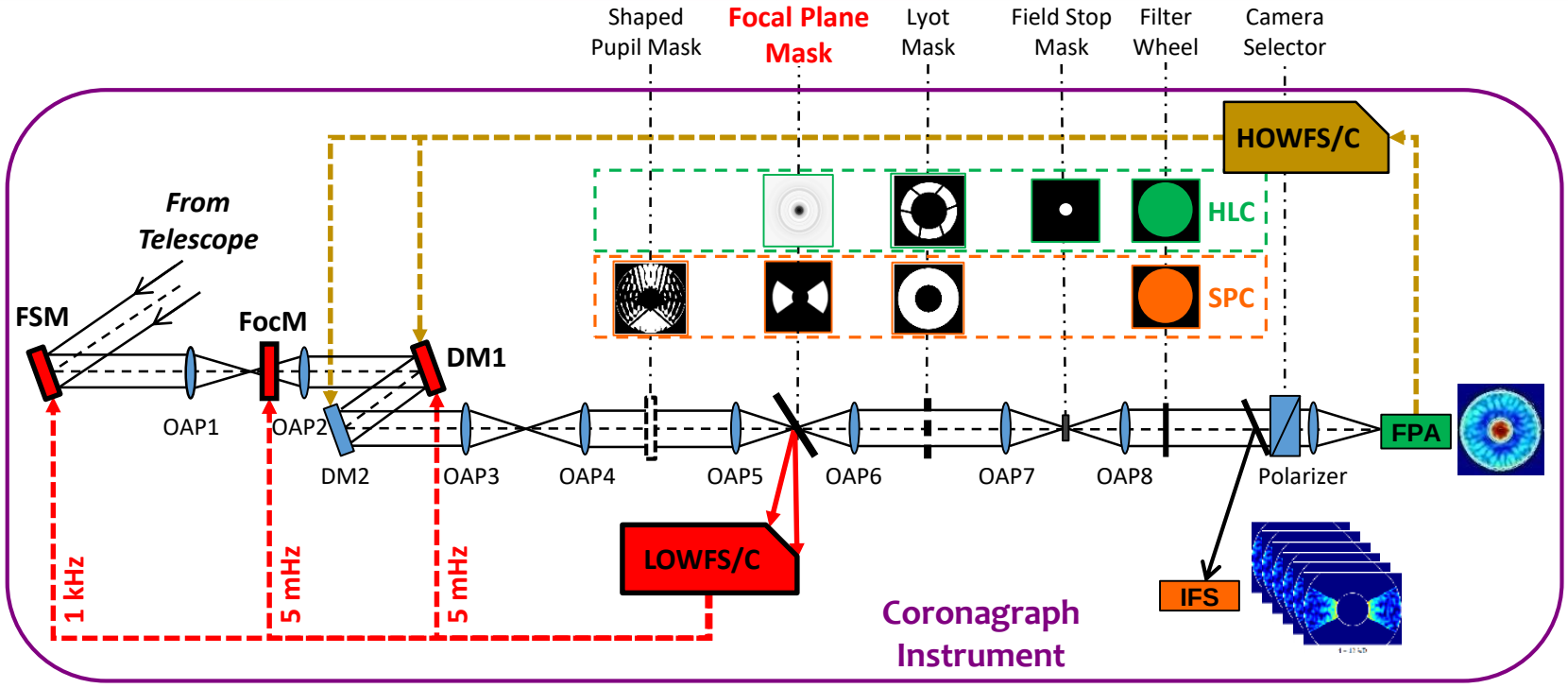
Shaped Pupil Disk Science Mask
ID: ERP25-3 installed on 06/29/2017

Conclusion and Future Work

- **WFIRST coronagraph technology development testbeds have be very successful and effective in developing and demonstrating needed technologies for WFIRST CGI**
- **WFIRST technology development milestones for 2017 have done and those for 2018 are on track**
- **Key testbed milestones for 2018**
  - Finish disk science SPC mask test including model matching
  - Coronagraph and LOWFS/C demonstration with photon flux equivalent stellar magnitude, Mv = 2 for EFC, and Mv = 5 for LOWFS/C
  - Improve the ISF 18% high contrast to match the requirement specified by CGI system engineering, which is ~5e-9.
  - Test LOWFS/C with WFIRST Phase A line-of-sight jitter which includes disturbances from multiple reaction wheels

Backup

WFIRST CGI LOWFS/C Overview



- LOWFS/C subsystem measures and controls line-of-sight (LoS) drift and jitter as well as the thermally induced low order wavefront drift
  - LoS: drift (< 2 Hz): ~14 mas, tonal jitter: ≤14 mas
  - WFE: drift (~10^{-3} Hz): ~0.5 nm (RMS), dominant by focus, astigmatisms and comas from the telescope optics rigid body motions
- Uses rejected starlight from occulter which reduces non-common path error
- Differential image wavefront sensor referenced to coronagraph wavefront control (HOWFS/C using EFC): maintains wavefront established for high contrast
- LOWFS/C telemetry can be used for coronagraph data post-processing

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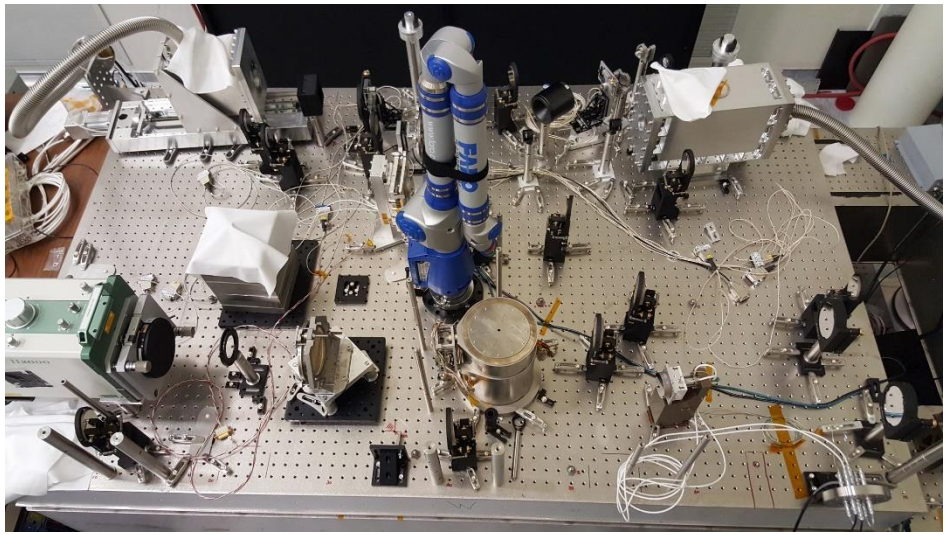
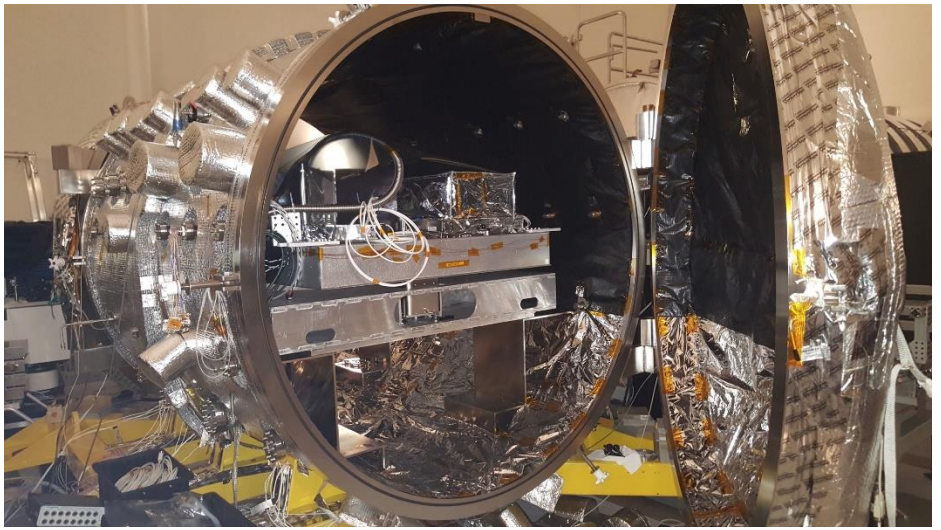
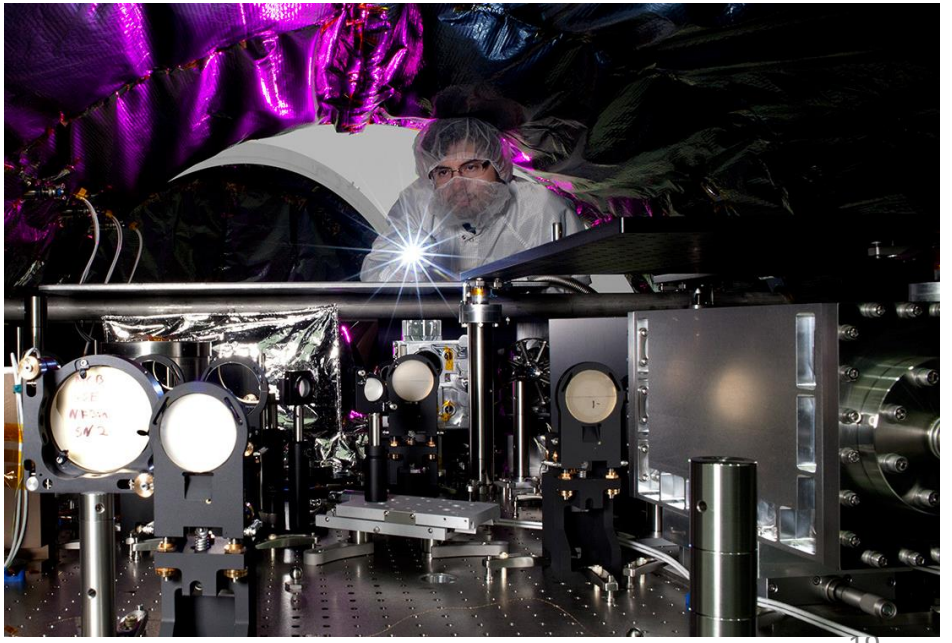
OMC Dynamic Testbed



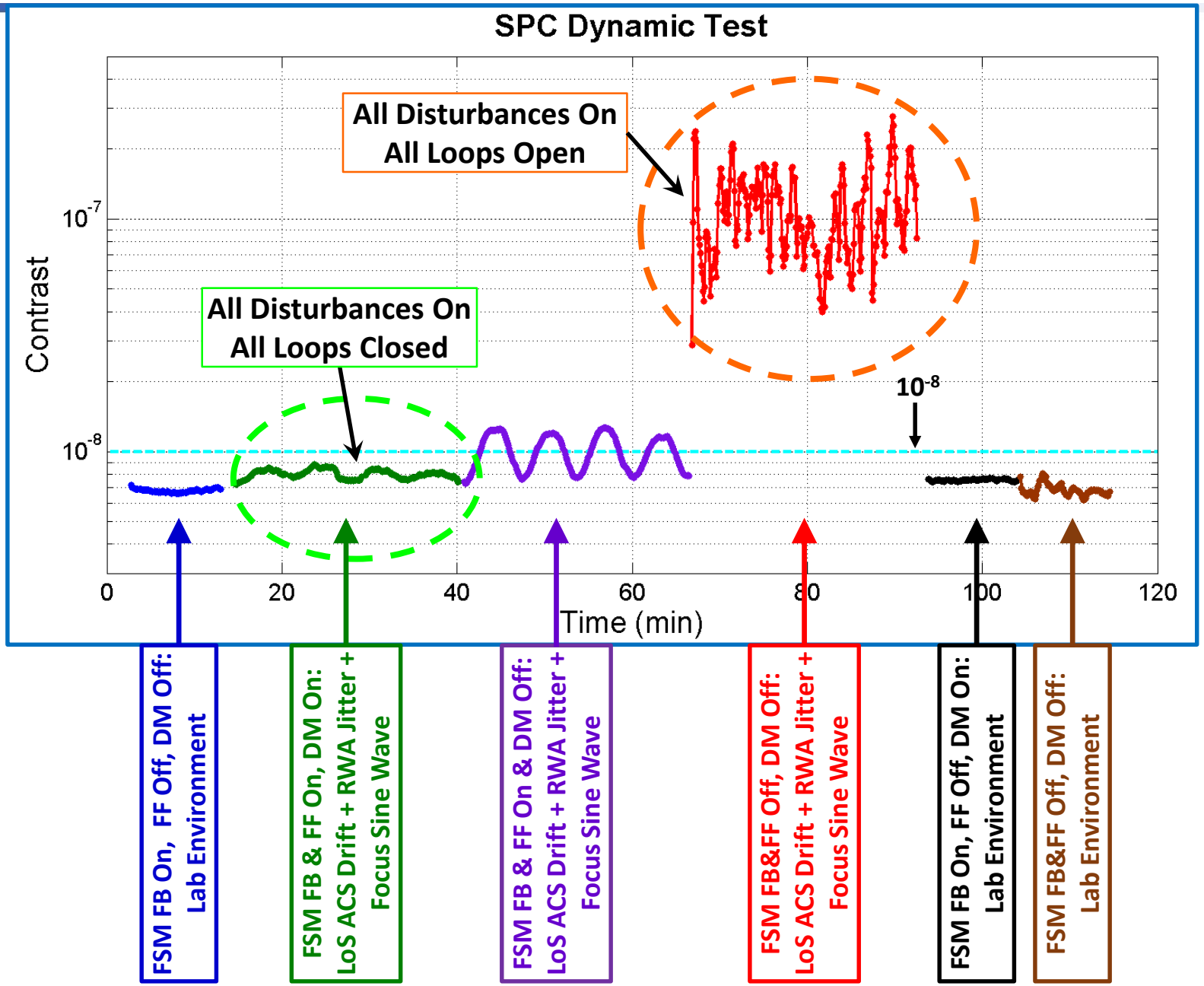




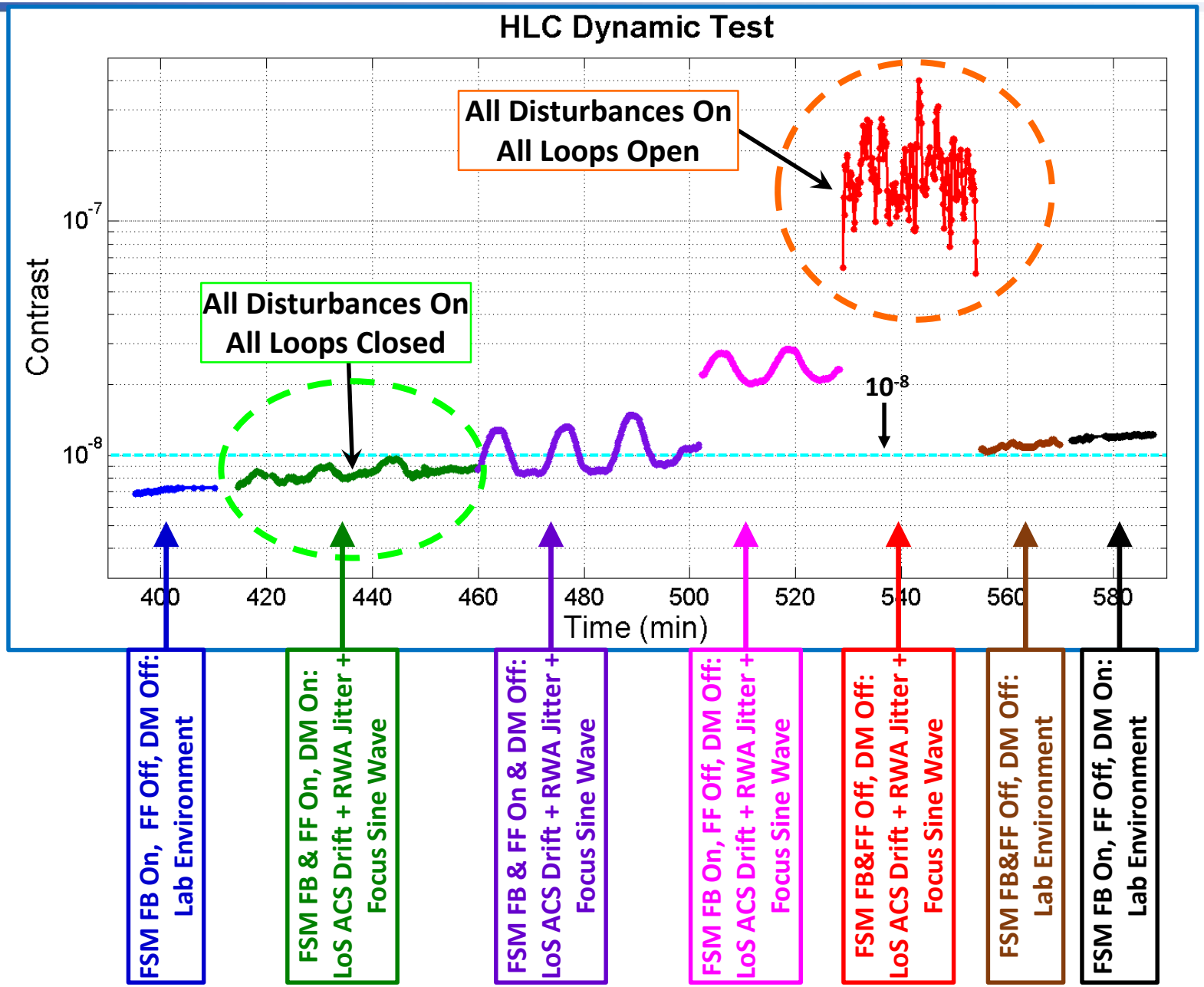
Testbed Dynamic Test: Disturbances

- **HLC/SPC dynamic test uses OTA-S to generate pointing and focus disturbances that WFIRST would experienced on-orbit.**
- Coronagraph Modes: Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
  - 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: ±1 nm (SPC) and ±0.5 nm (HLC) focus disturbance. The amplitude is 4X and 2X worse than expected WFIRST thermal drift.
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec (12.5 min). The focus disturbance is much faster (~100X) than anticipated WFIRST thermal drift speed
  - Focus corrected by one of OMC's deformable mirrors (DM).

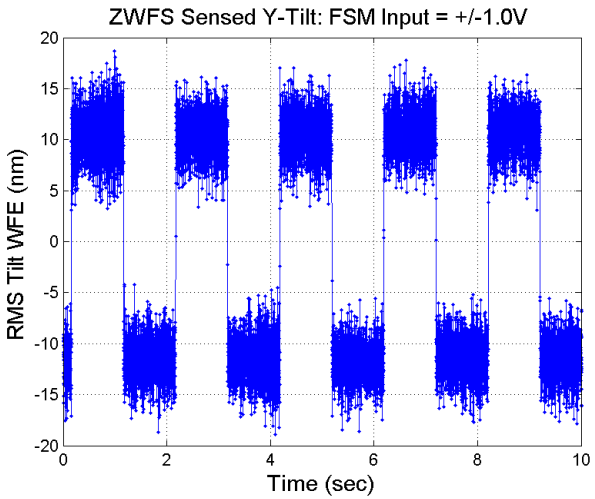
SPC+LOWFS/C Dynamic Test Result

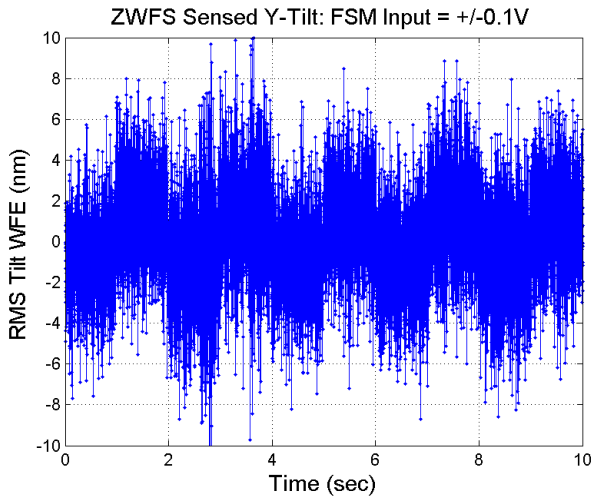


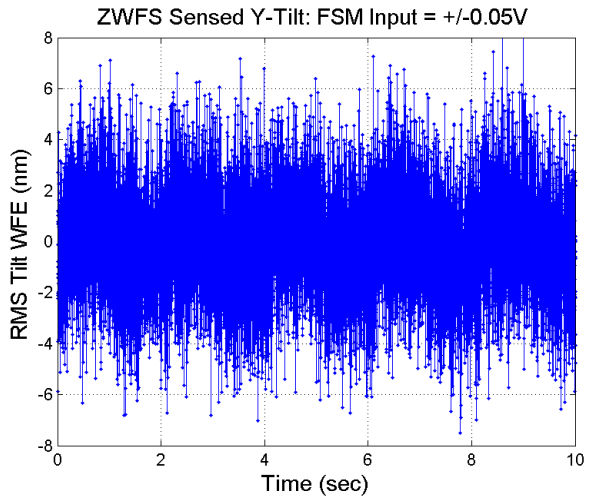
HLC+LOWFS/C Dynamic Test Result

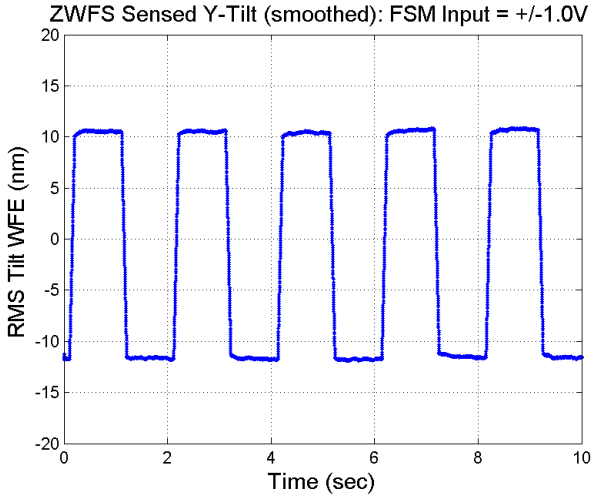


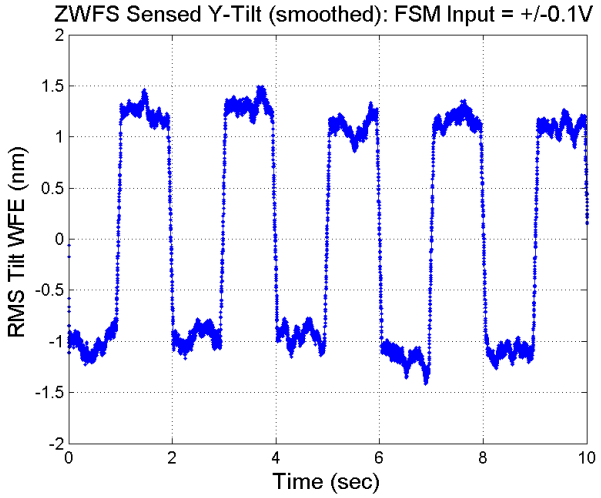
LOWFS Sensitivity: Line-of-Sight

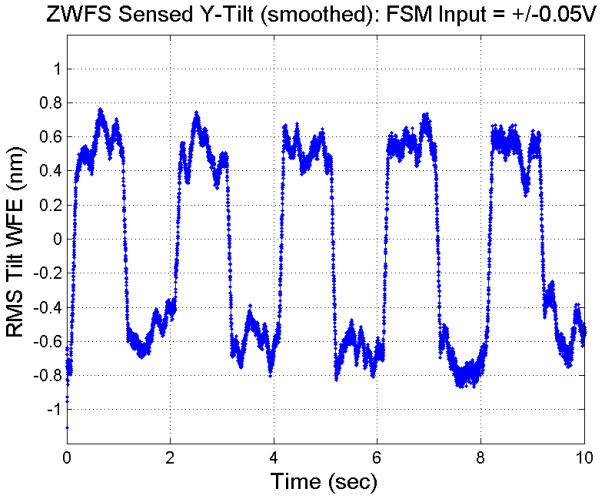












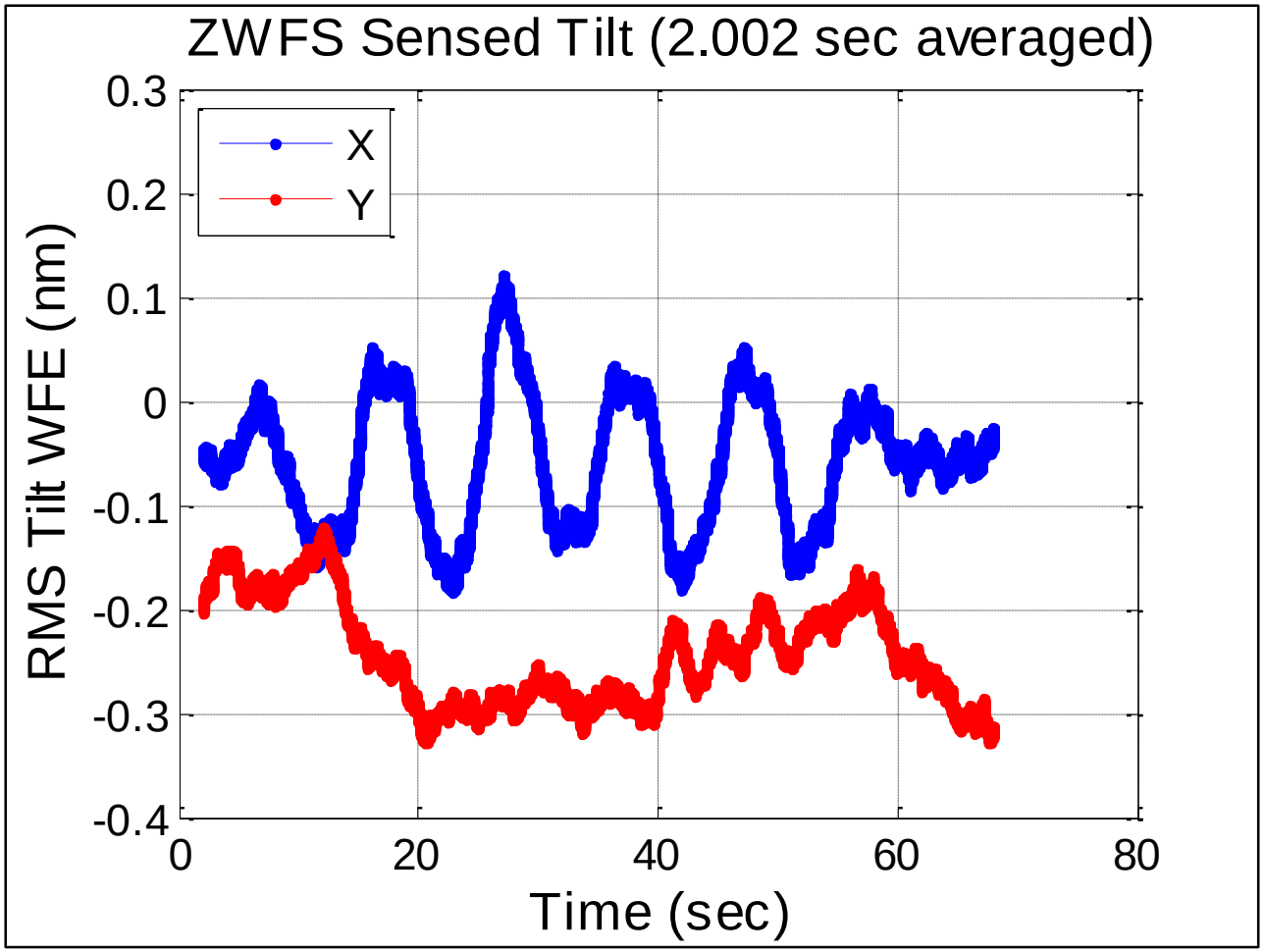
Mean Sep = 22.1 nm (7.7 mas)

Mean Step = 2.2 nm (0.77 mas)

Mean Step = 1.2 nm (0.38 mas)

- Sensor clearly detects ±0.2 mas on-sky signal (right column)
- ZWFS sensed tilt WFE matches calibrated input to within 8%

Recent FSM Chopping Test: Preliminary

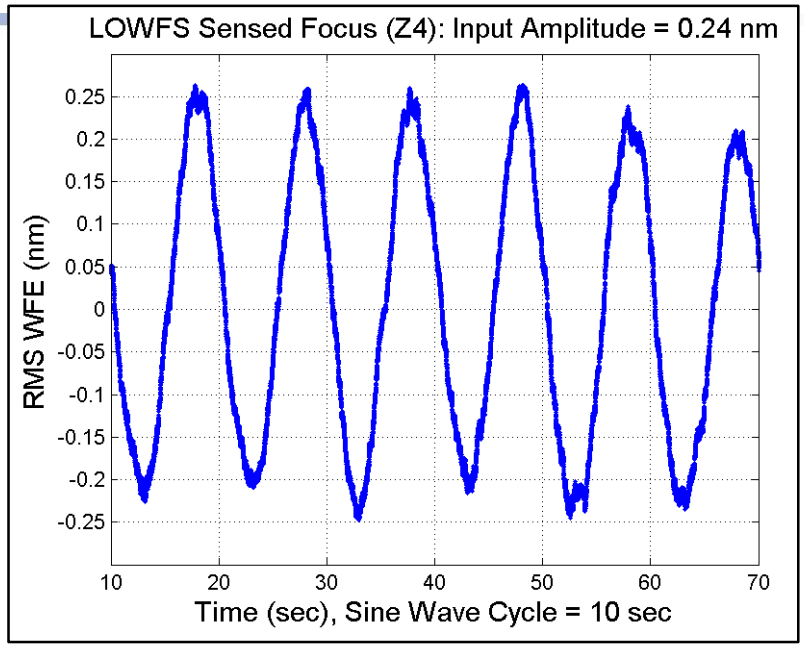


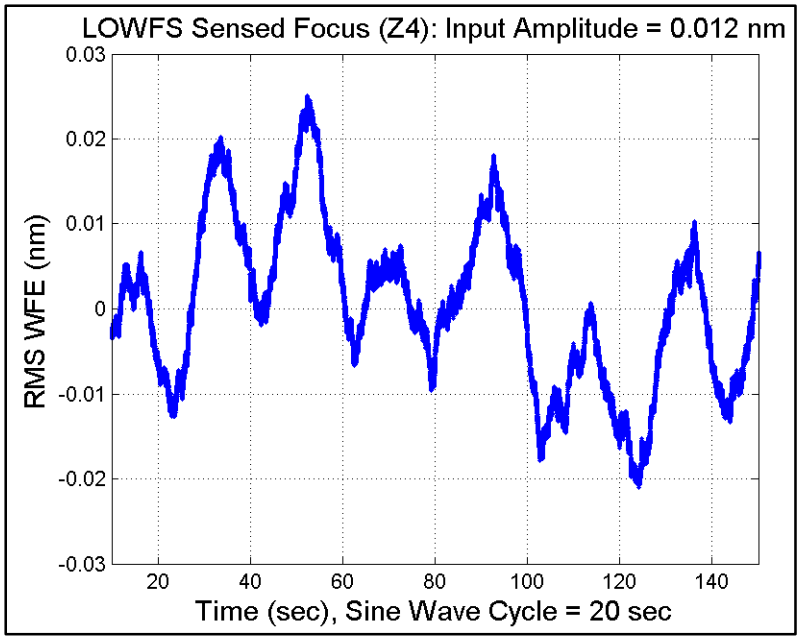
- **FSM Ch 1 (X tilt) is chopped**
- **LOWFS can sense LoS as small as 0.1 nm, which is 0.01 mas for WFIRST**

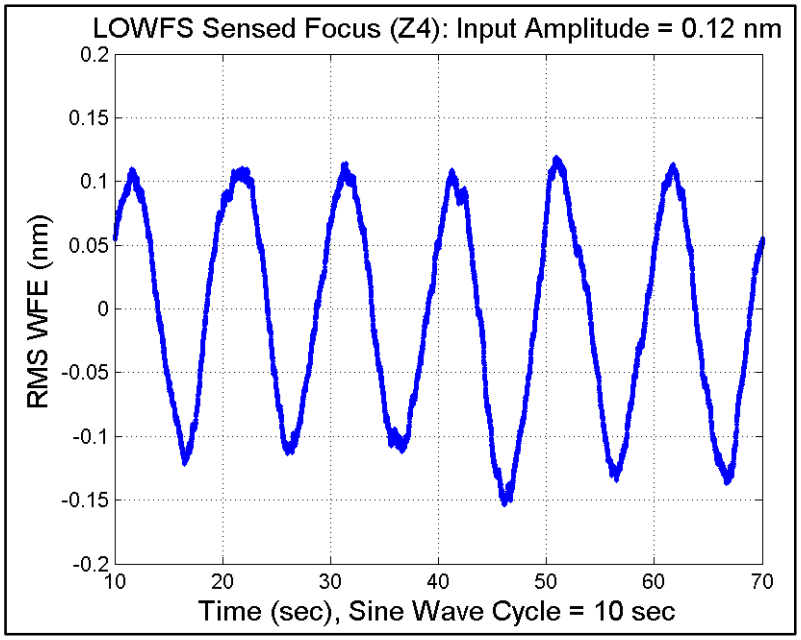
LOWFS Sensitivity: Focus

- **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)!**



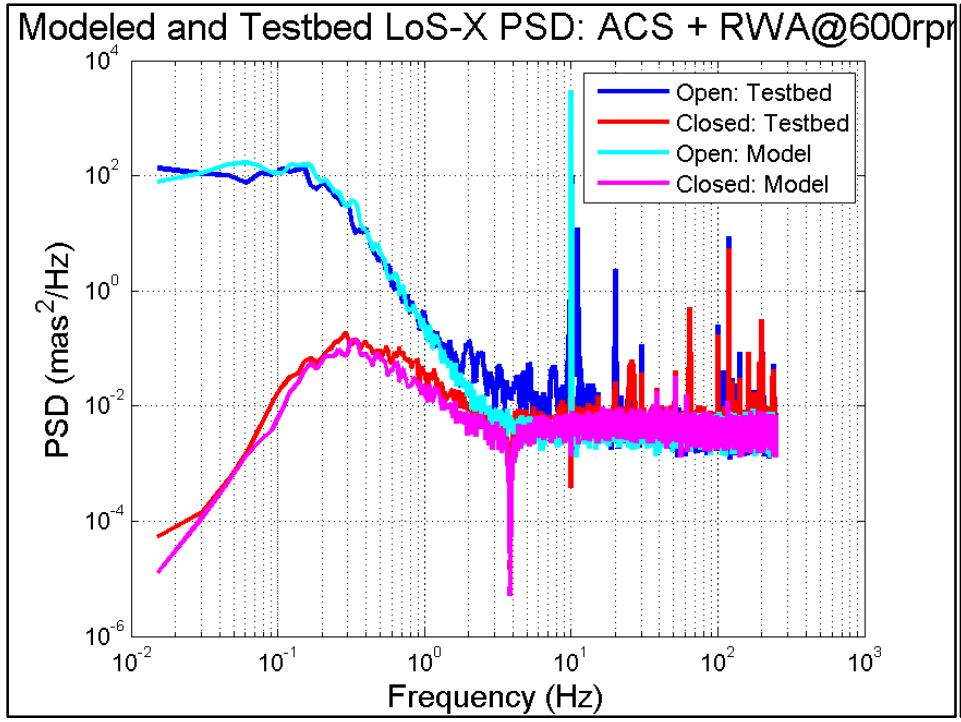


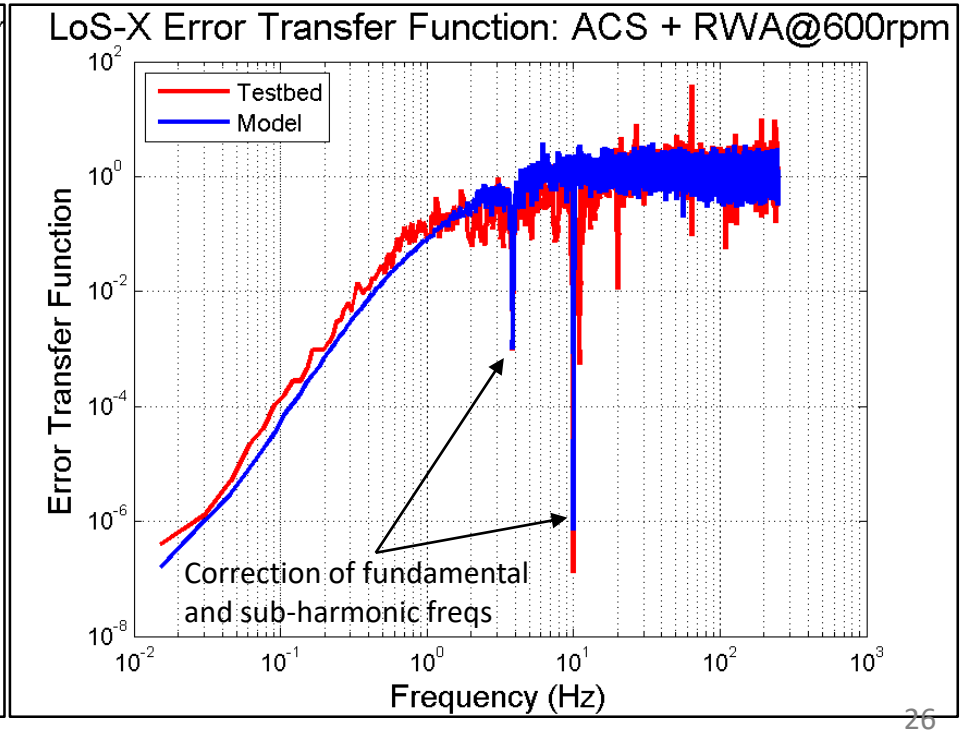


LOWFS/C FSM Loops Performance: Data vs. Model

- **Modeled and testbed PSD of open/closed loop in LoS X (lower right plot)**
  - Cycle 5 ACS drift and jitter at wheel speed of 600 rpm (fundamental freq = 10 Hz)
  - 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)**
  - Feedback loop forms high pass filter
  - Feedforward loop forms notch filters at fundamental and sub-harmonic frequencies

- **Excellent agreement between modeled and testbed data for FSM loops**

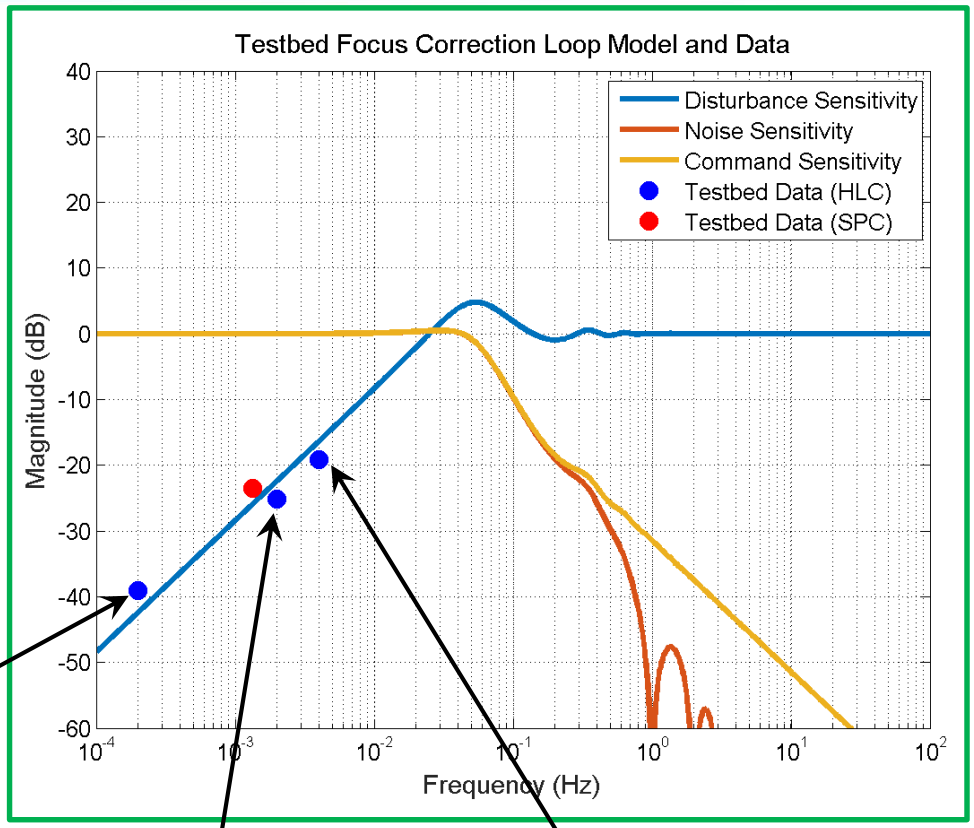


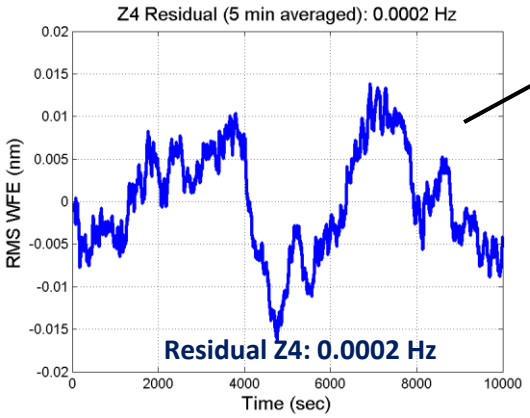


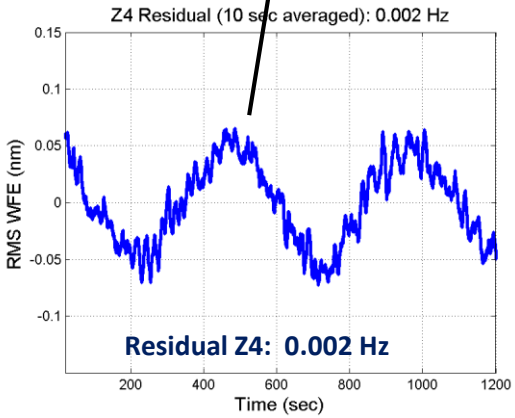
LOWFS/C DM Loop Performance: Data vs. Model

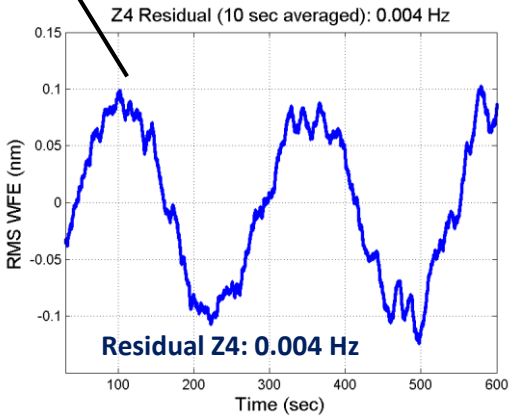
- **Focus drift generated by OTA simulator**
  - 2 nm P-V sinusoidal focus disturbance
  - 4X larger than WFIRST flight
- **DM is used to correct focus**
- **Solid lines are model prediction**

- **Excellent agreement between modeled and measured DM loop performance**



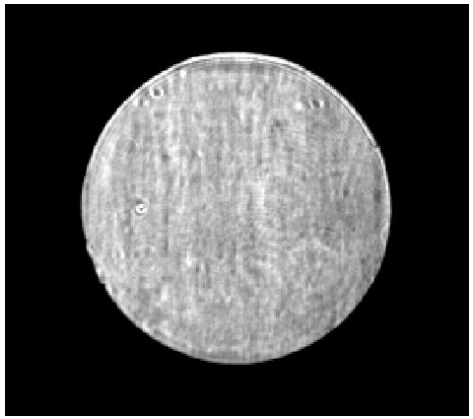




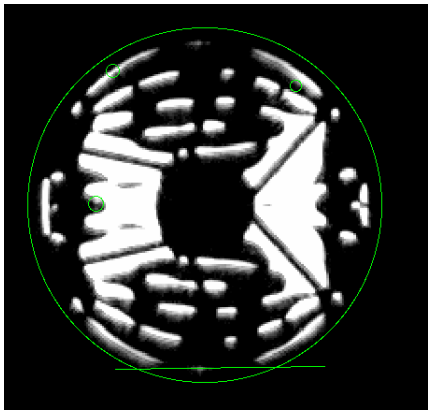


SPC/IFS Test Configuration

Pupil

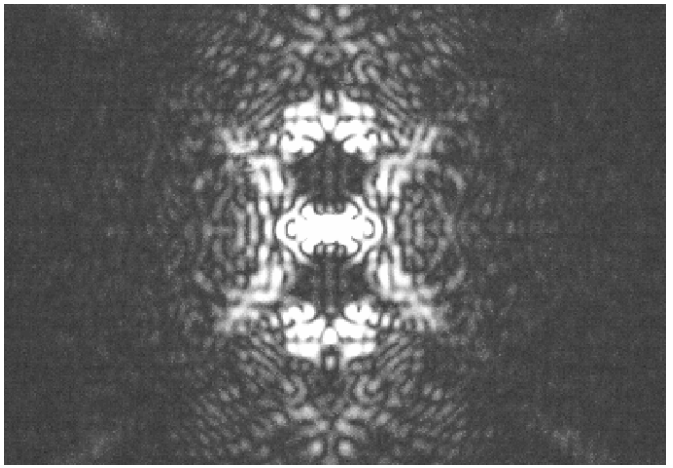


Mask



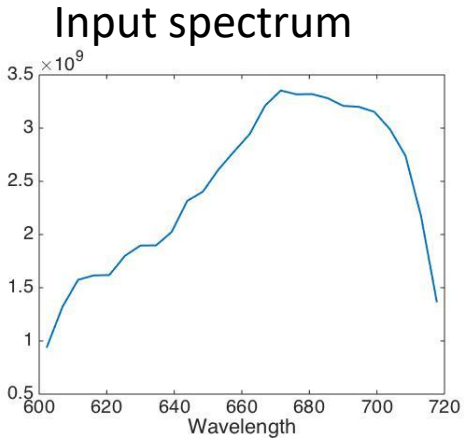
Mask + Lyot

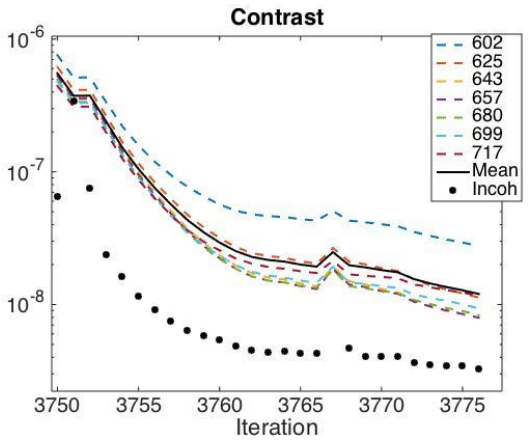
PSF

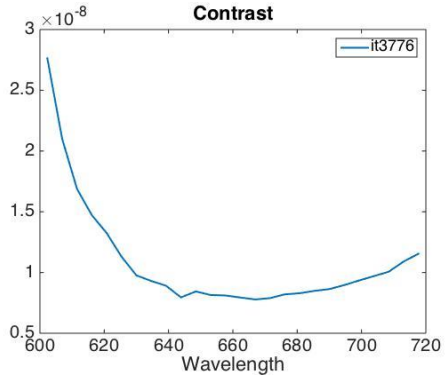


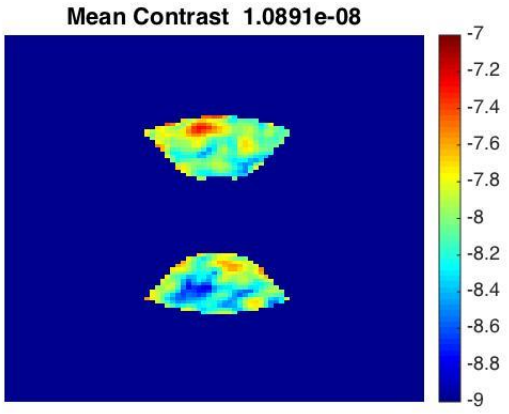
- **Pupil errors are behind the SP mask.**
- **SP mask has small Low Order error.**

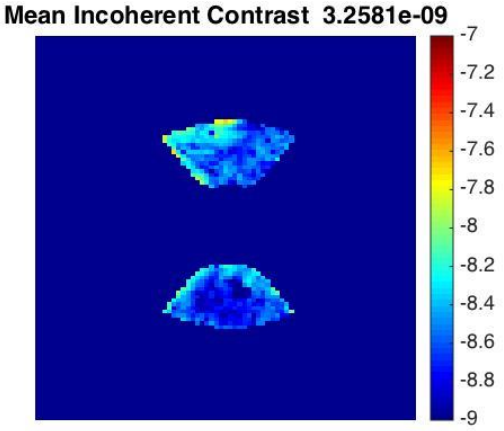
Run Broad band 18%, IFS

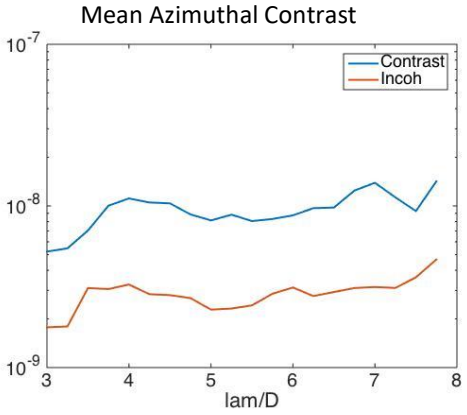






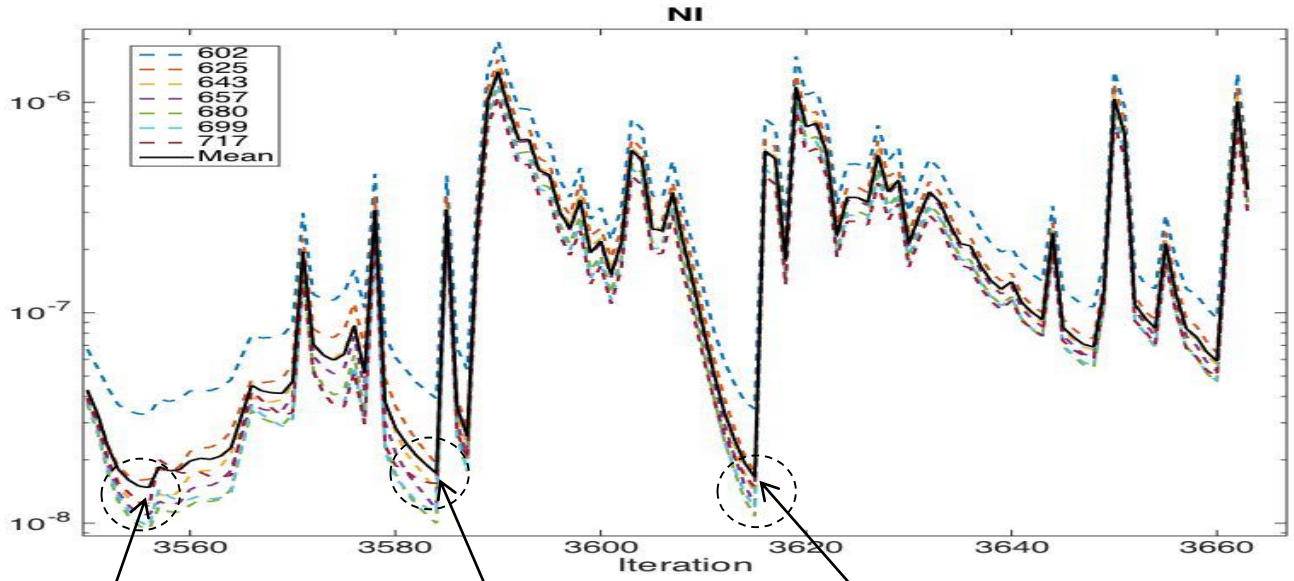


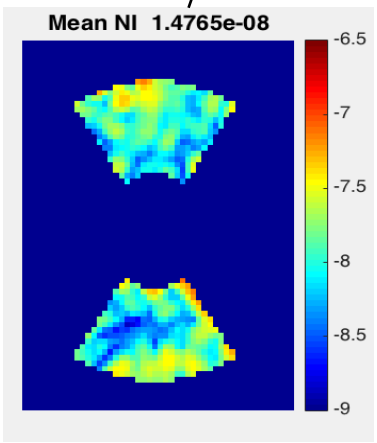


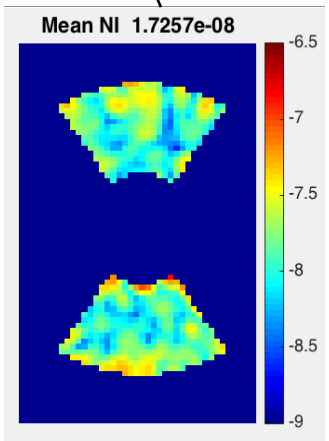


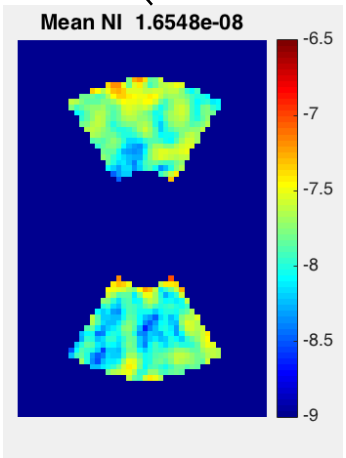
- 18% Control at 660nm
- Score: Two sides, 26 channels, 3-8 lam/D, 65^0
- Control: Two sides, 7 channels, 2.5-9.5 lam/D, 75^0
- PISCES optimal extraction

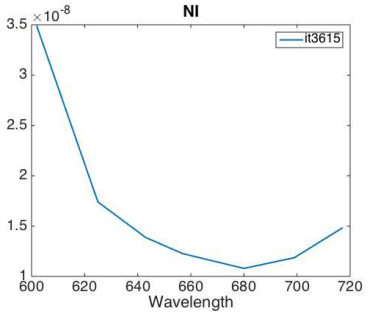
Full Run May 15, SPC_IFS





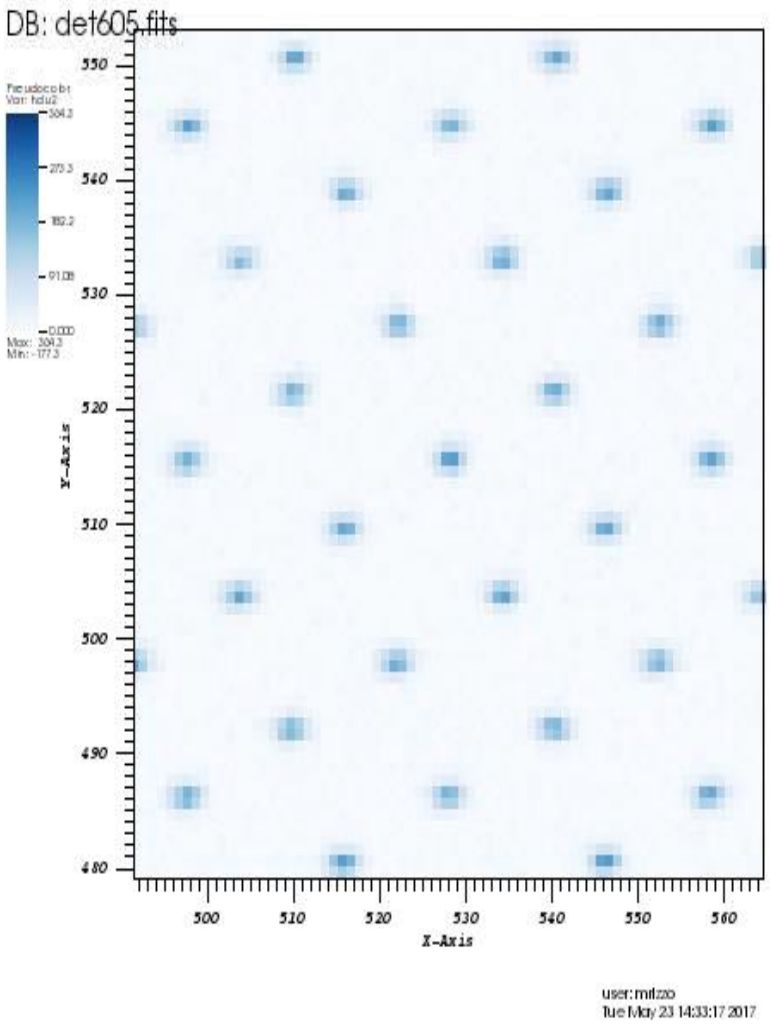


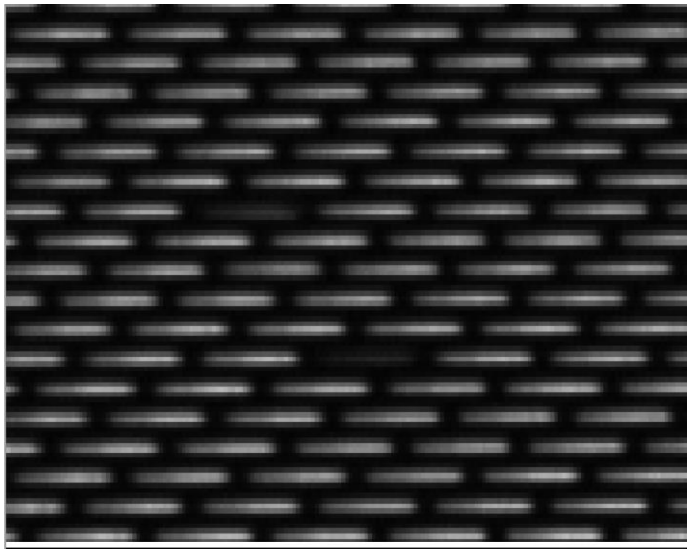




- 18% Control at 660nm

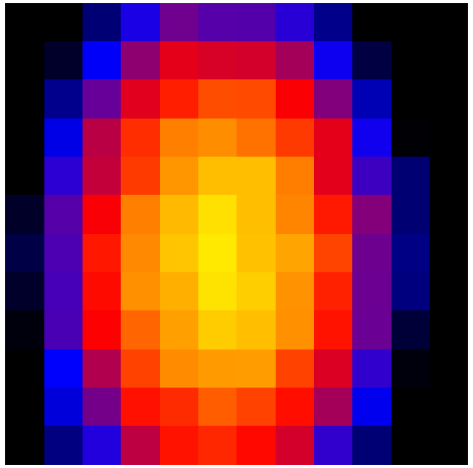
IFS (PISCES) Microspectrum





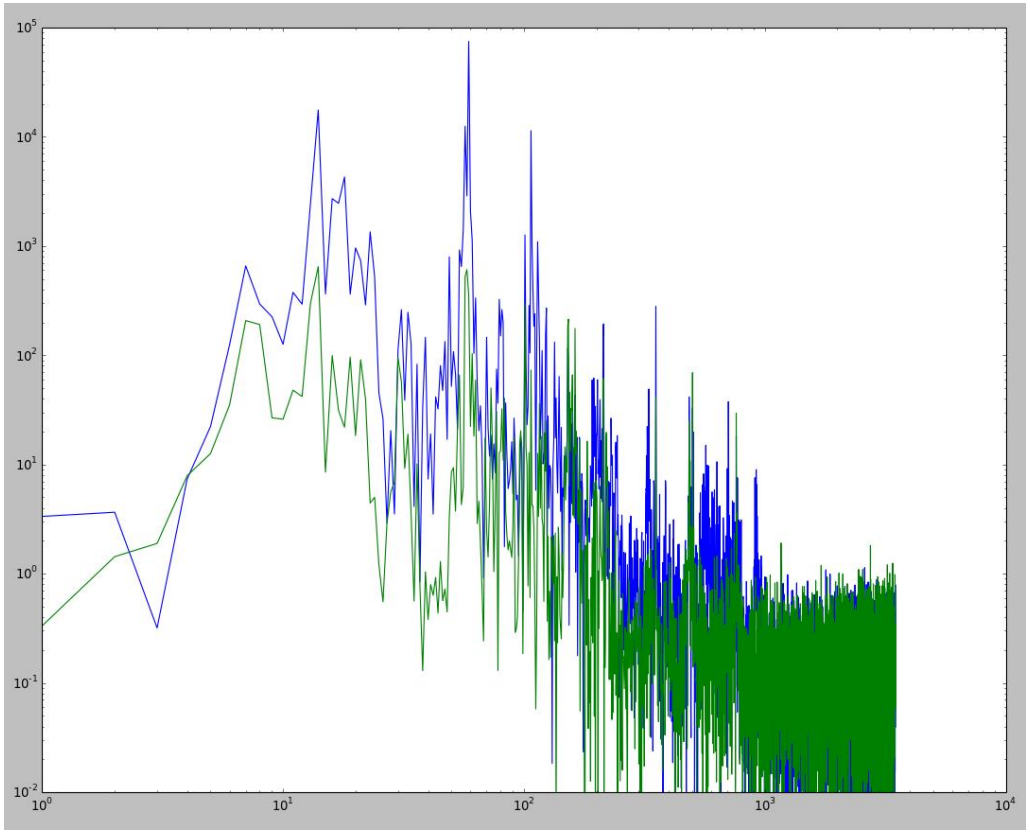
SPC/IFS Testbed Jitter Measurement

Centroid



High speed image centroid is used to measure the testbed line of sight jitter

LoS Jitter PSD: unit = pixel



Jitter: (0.08,0.017) pixels rms