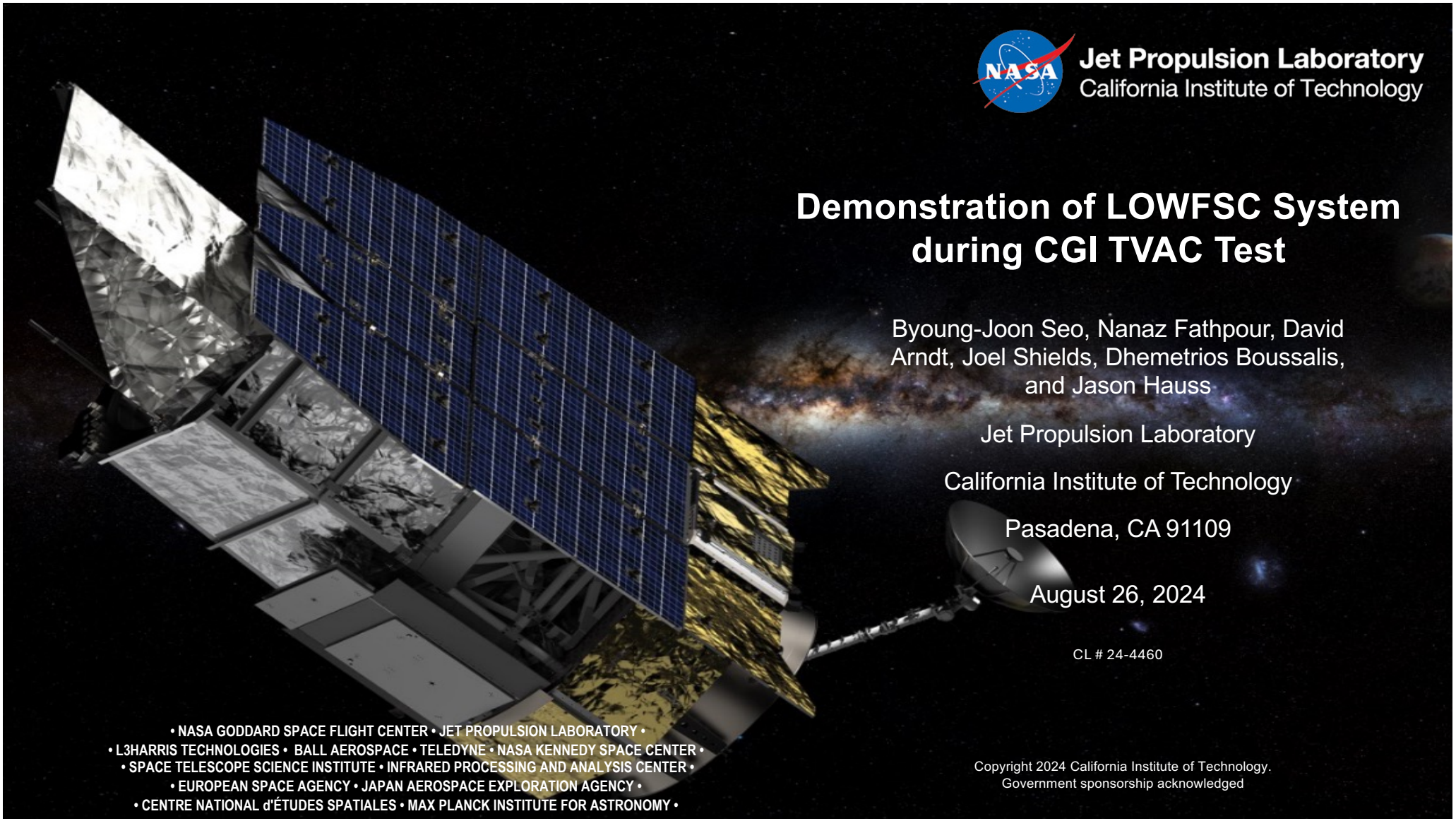

Jet Propulsion Laboratory
California Institute of Technology

Demonstration of LOWFSC System during CGI TVAC Test

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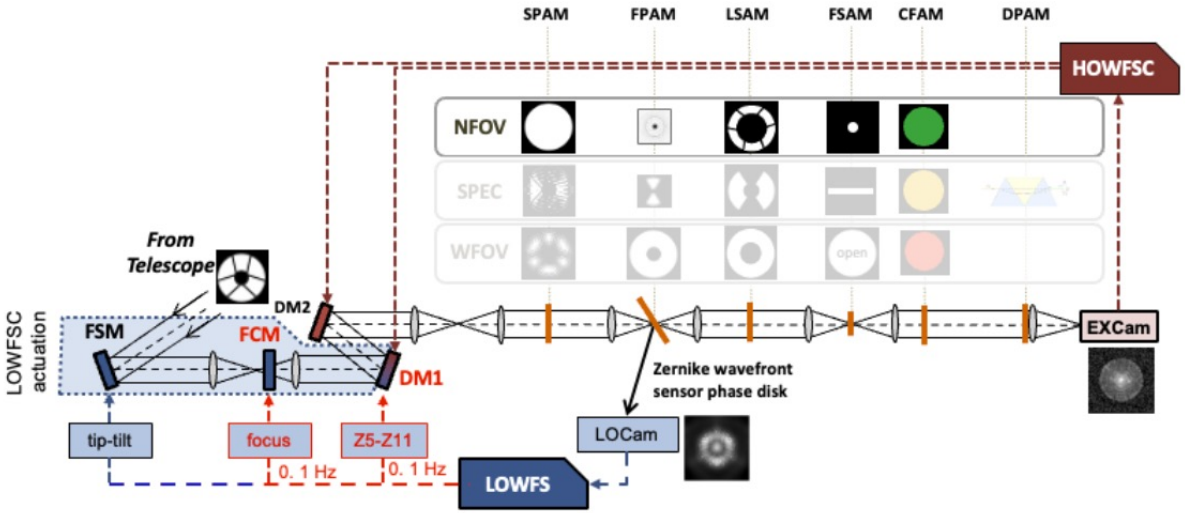
Outline

- Overview of CGI LOWFSC System
- LOWFSC demonstration for in-orbit-like operation scenario
  - CGI perturbed by STOP-model predicted wavefront perturbation (OS10)
- Frequency analysis & Comparison with Requirements
- Summary

Overview of CGI LOWFSC system

- Line of Sight Control Loop (**LCL**)
  - Fast control
  - Result presented by M. Mandic & B. Kern.
- Focus Control Loop (**FCL**) & Zernike Control Loop (**ZCL**)
  - Slow control
  - Subject of this presentation.
  - First-ever system-level test during TVAC.

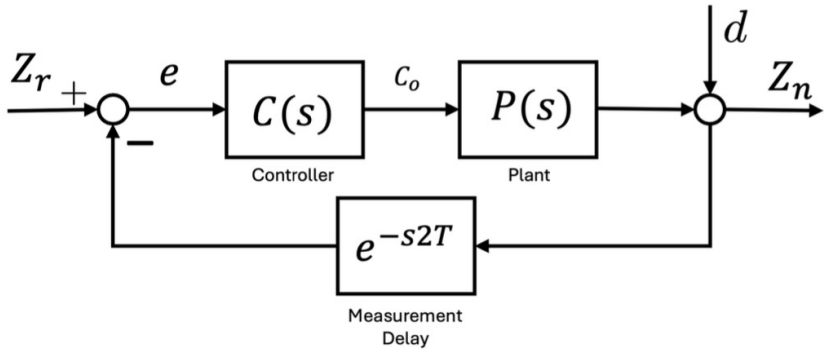


LOWFSC Control	Modes Corrected	Actuator	Controller Sampling Rate [Hz]	Controller Bandwidth [Hz]
Line of Sight Control Loop (LCL)	Z2, Z3	FSM	1000 Hz	20 Hz
Focus Control Loop (FCL)	Z4	FCM	0.1 Hz	1.6×10^{-3} Hz
Zernike Control Loop (ZCL)	Z5,Z6...Z11	DM1	0.1 Hz	1.6×10^{-3} Hz

Design Principle for FCL & ZCL

- Design Principle
  - Each Zernike control is independent.
  - Each Z5-Z11 control architecture is identical but different from Z4 controller due to different plant, *P(s)*; DM vs FCM
  - Controllers, *C(s)*, are implemented in CGI FSW with control parameters are saved in MRAM.
  - Measurement delay of 20 seconds.

- NOTE:
  - No external stimuli (d) is available for test for Z4-Z11.



- Z_r : Zernike Set Point
- d : Disturbance
- Z_n : Zernike Control Output
- T : Control Cadence of 10 Seconds
- C(s) : Controller Transfer Function
- P(s) : Plant Transfer Function

Zr – d = Zn @ steady state

Tests Conducted during TVAC

- Total 6 different tests are conducted for TVAC 5 shifts.
- Step Input Response Tests are for visualization purpose
- Schroeder Input Response Test are for frequency analysis and requirement validation.
- OS10 STOP model predicted wavefront disturbance is used for demonstration of likely in-orbit operation scenario.

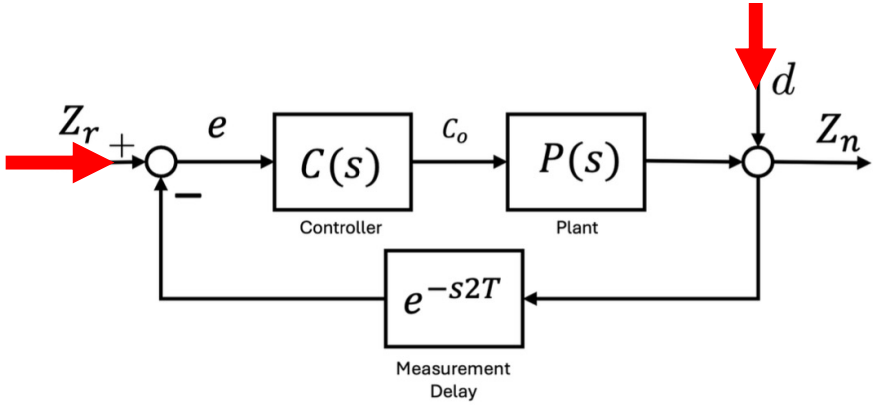
Test No	Test Title	Description & Objective	Zernike Control
Test 1	**Z4** test for **external Step** input	Visualize Z4 performance	OPEN
Test 2	**Z4** test for **external Schroeder** input	Frequency analysis of Z4 performance	OPEN
Test 3	**Z4-Z11** test for **internal Step** input	Visualize Z4-Z11 performance	CLOSED
Test 4	**Z7** test for **external Step** input	Visualize Z7 performance	CLOSED
Test 5	**Z5** test for **external Schroeder** input	Frequency analysis of Z4 performance	CLOSED
Test 6	**Z4-Z11** test for **external OS10** input	Demonstration of likely in-orbit scenario	CLOSED

- NOTE:
  - Z2,Z3,Z4 (LCL & FCL) are closed during all tests.
  - HOWFSC is not running during all tests.

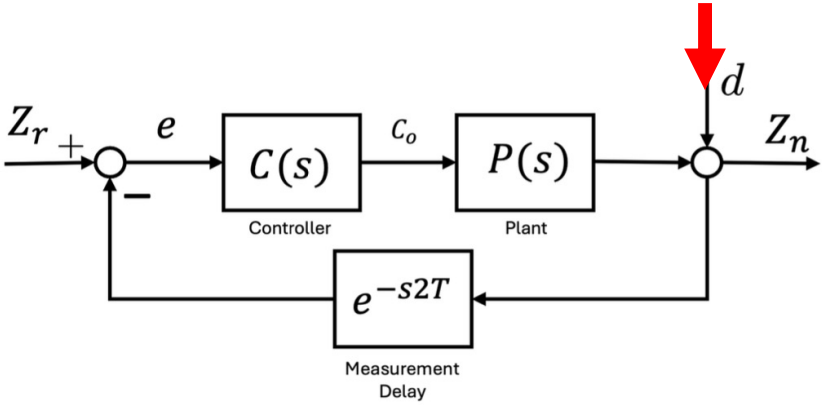
FCL : Focus Control Loop
ZCL : Zernike Control Loop
Schroeder : designed input signal for frequency analysis

Internal vs External Perturbations

- Internal Perturbation
  - Wavefront change due to DM or FCM change.
  - Caused by intended DM/FCM changes during HOWFSC, which LOWFSC should not remove.
  - It is known perturbation, introduces both Zernike set point (Zr) and disturbance (d) change.
  - Fast response is designed, (Alka Feed-Forward)



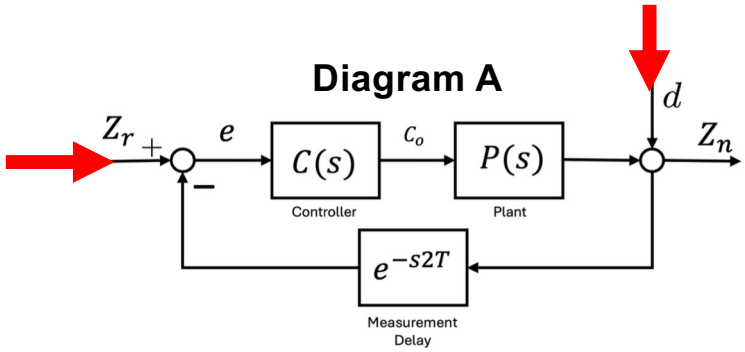
- External Perturbation
  - Wavefront change without DM or FCM change.
  - Caused by OTA input or unintended.
  - It is unknown perturbation, introduces only disturbance (d) change.
  - Slow response is designed.

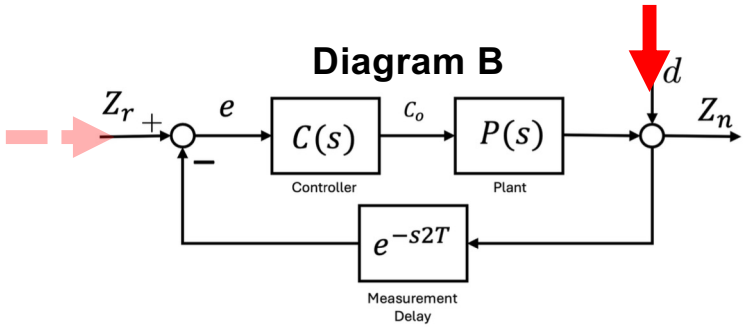


Perturbation Injection

- Injection of Internal Perturbation
  - Use DM1 (Diagram A)
  - NOTE: DM2 internal perturbation test has not been tested.

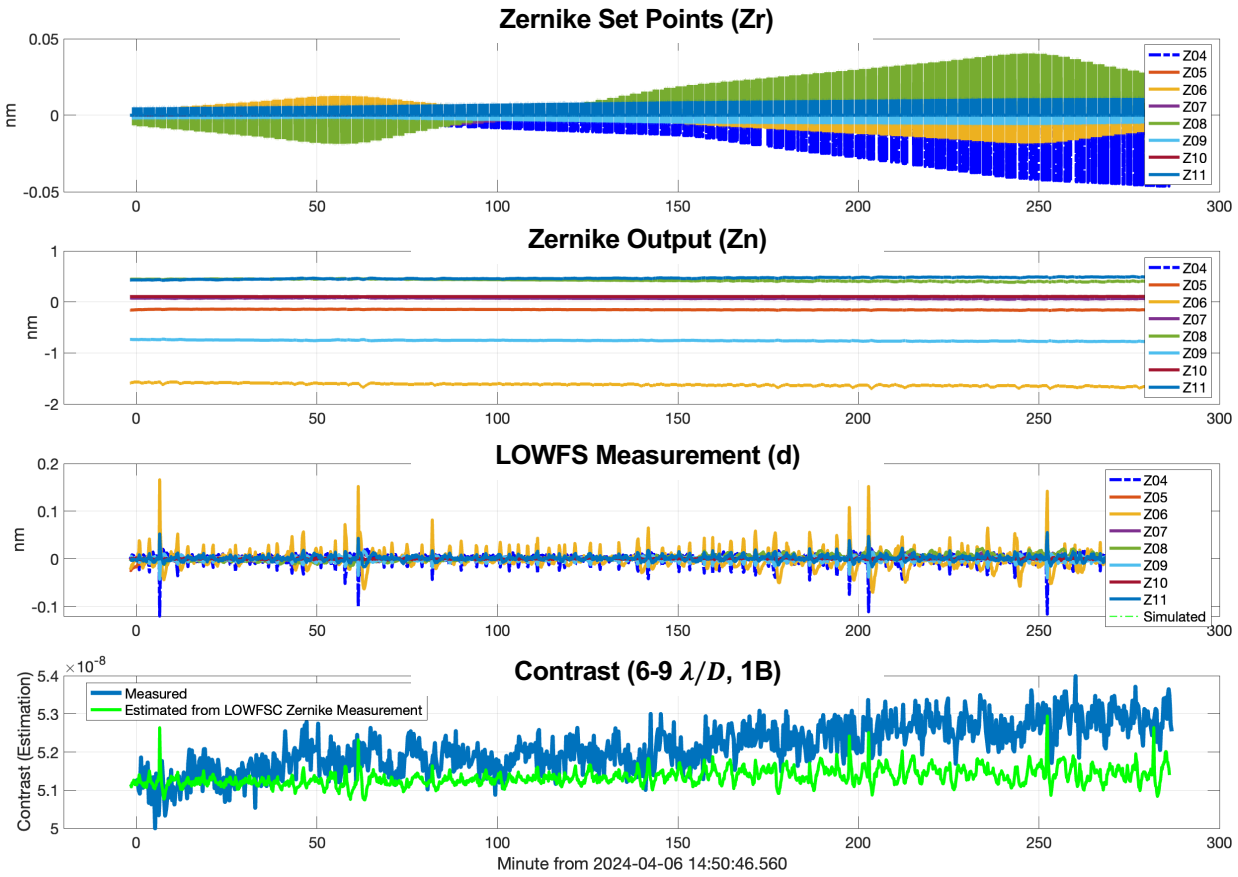
- Injection of External Perturbation
  - No external stimuli (d) is available. Alternative approaches needed.
  - Use following step to mimic the external perturbation. (Diagram B)
    - Record current *Zr*
    - Move DM1 to apply external wavefront change.
    - Restore *Zr*
  - NOTE: We chose DM1 to inject the perturbation over DM2 to avoid unnecessary complication raised by the DM1/DM2 inconsistency issue.





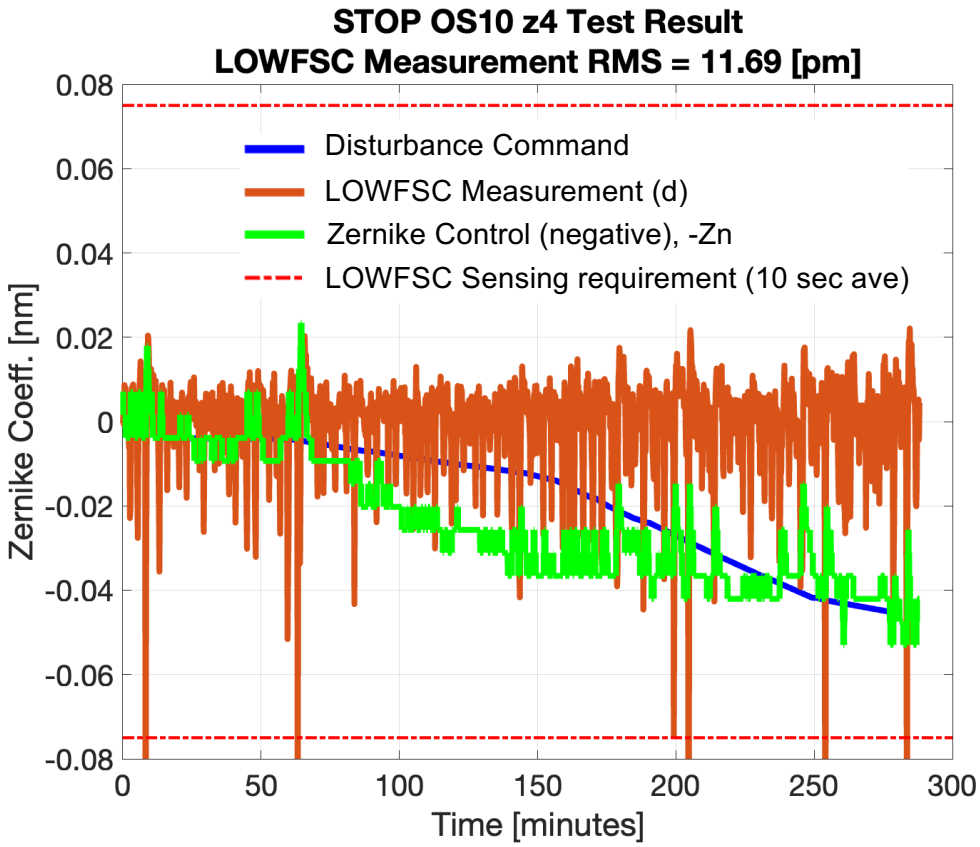
OS10 STOP model Disturbance Test (1/3)

- Test Objective
  - To demonstrate Likely In-Orbit Scenario
- Test Setup
  - All LCL/FCL/ZCL CLOSED
  - Inject OS10 perturbation via DM1
  - Original OS10 signal input is ~190 hrs long, tailored into ~ 5 hrs.
- OS10 input are as small as ~ few tens of picometers RMS.
- Contrast drift of 2E-9 over ~ 5 hrs is observed. But not clear if this is control residual, cross-talks among Zernikes or other higher order drift.



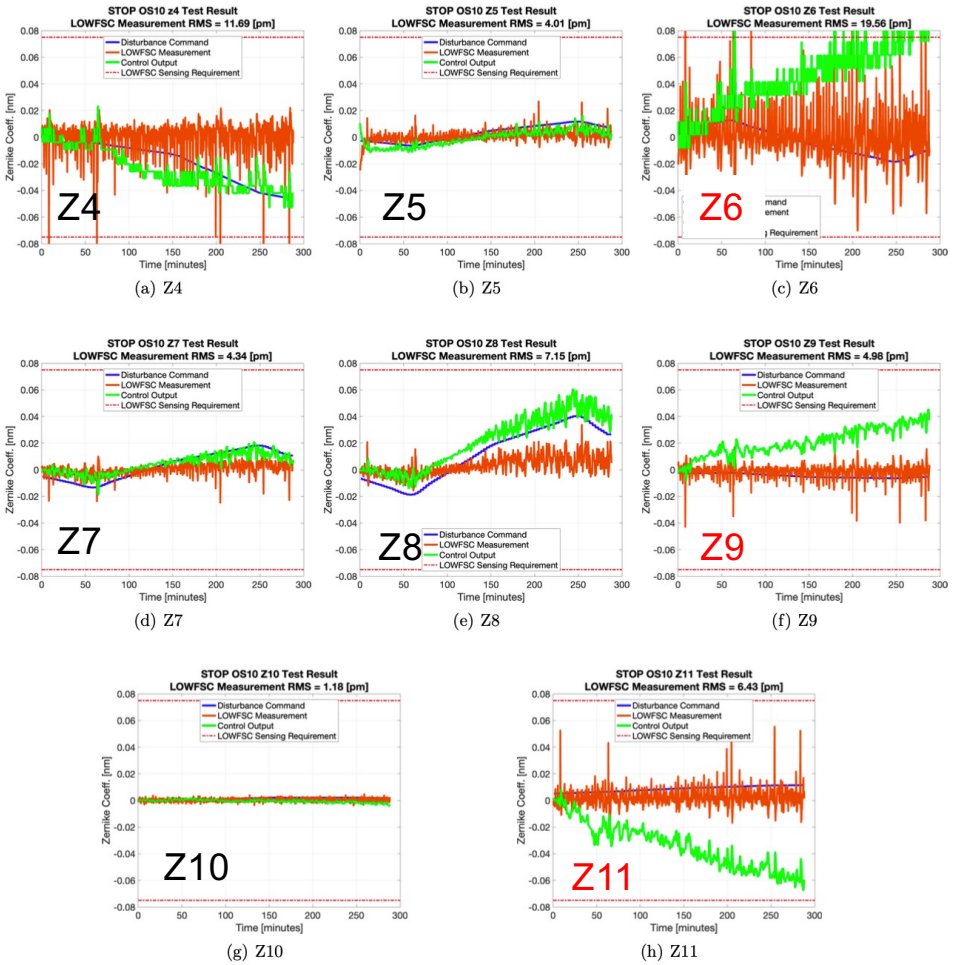
OS10 STOP model Disturbance Test (2/3)

- For visualization purpose,
  - Z4 data are co-plotted.
  - Negative of Zernike Control (-Zn) was plotted to have the same sign with Disturbance command. Also biases removed. ➔ Ideally, they are on top of each other.
- RMS of LOWFS measurement error (10 sec average) is 11.69 pm, **meeting requirement** of 75 pm.
- Disturbance injections vs (negative) Zernike Control **match closely** within 20 pm ➔ LOWFC controls Z4 better than 20 pm.



OS10 STOP model Disturbance Test (3/3)

- RMSs of LOWFS measurement errors are **smaller than requirement** of 75 pm with margin for all Zernikes.
- Disturbance injections vs (negative) Control commands **match closely** as expected except for Z6, Z9, and Z11 ➔ LOWFC controls Zernikes better than 20 pm.
- The deviations of Z6, Z9, Z11 are order of ~ 10s of picometers over 5 hours ➔ Drift rate of TVAC environment.



(a) Z4 (b) Z5 (c) Z6

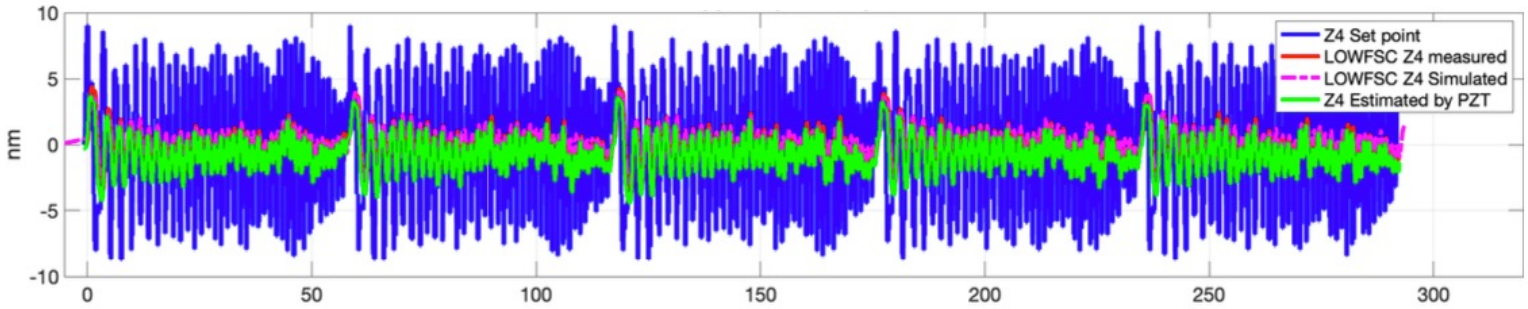
(d) Z7 (e) Z8 (f) Z9

(g) Z10 (h) Z11

Schroeder Input

- Schroeder signal has a broader frequency range and is efficient for characterizing the frequency response.
- Repeated long duration Schroeder signal is injected as the Zernike set point change (Zr).
  - Tested Z4 (FCL)
  - Tested Z5 only for ZCL

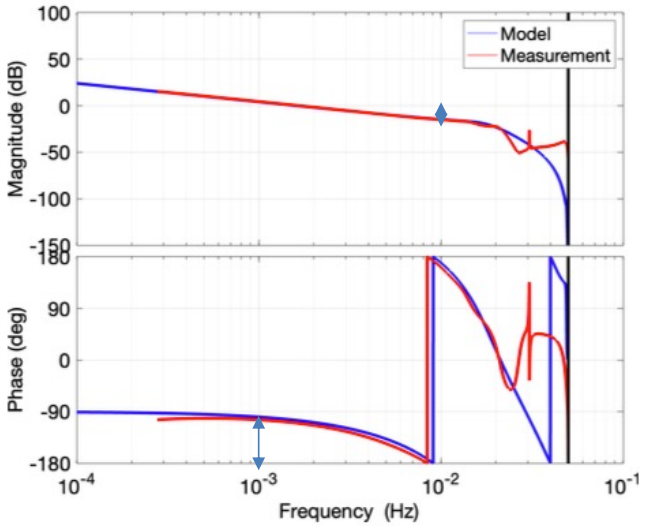
Schroeder Signal Injected for FCL Frequency Analysis



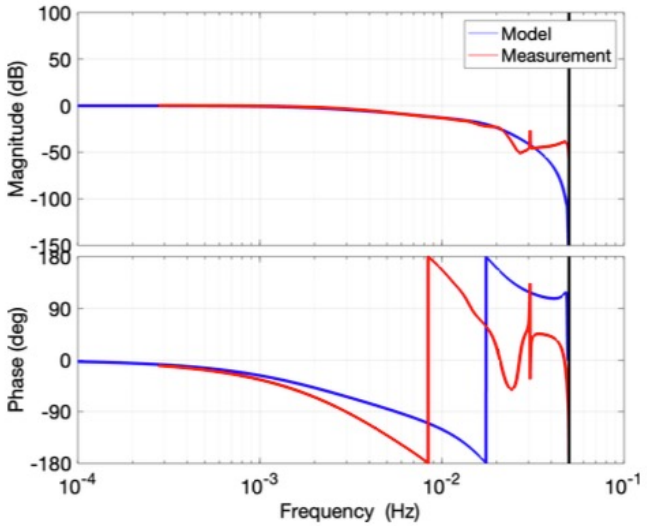
Time [minute]

Frequency Analysis for FCL LOWFSC Data

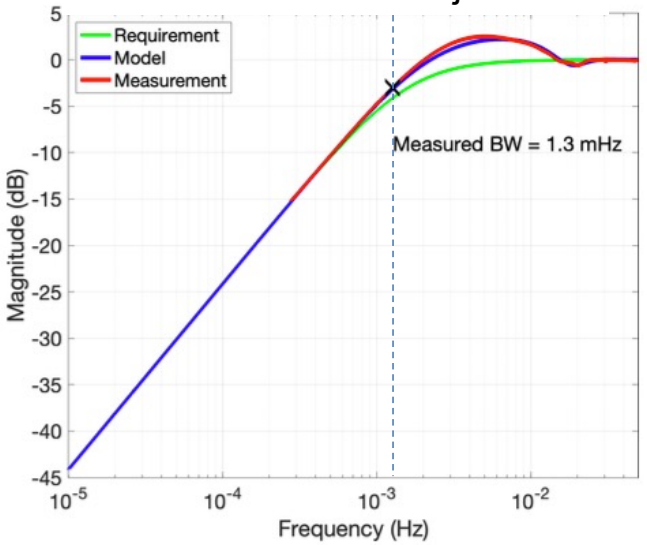
FCL Open Loop TF



FCL Closed Loop TF



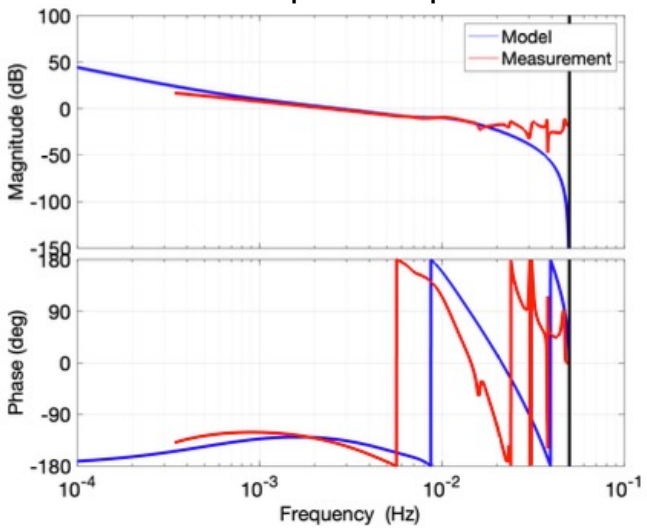
FCL Disturbance Rejection



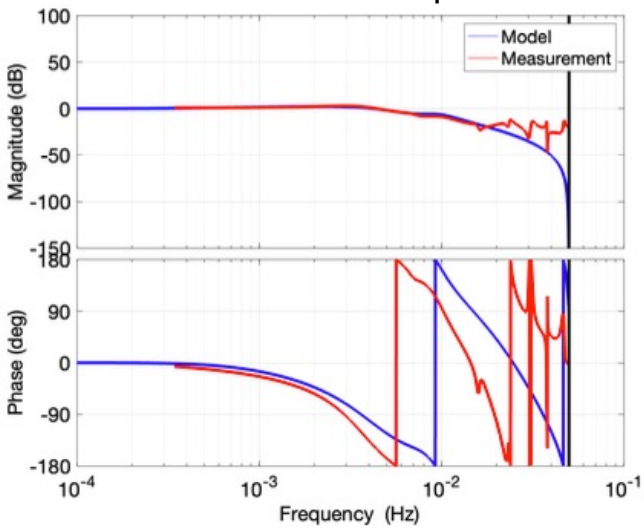
- Measurements are in **good agreement** with design values.
- Measurements **meet *(the sprit of)* their requirements**, as summarized in next page.

Frequency Analysis for ZCL (Z5) LOWFSC Data

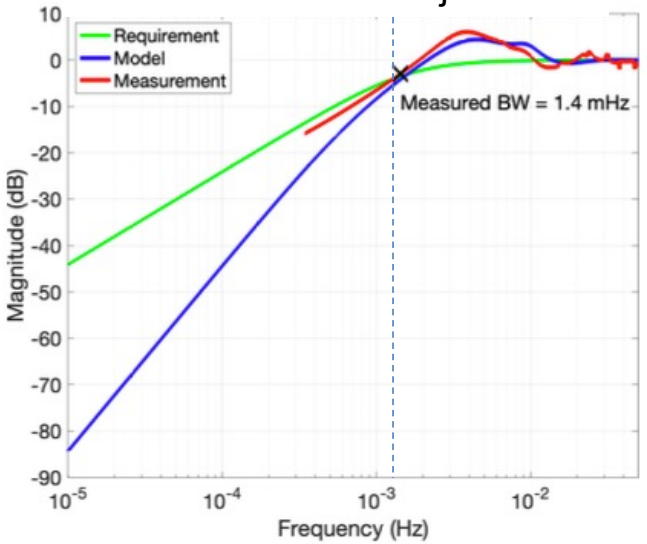
Z5 Open Loop TF



Z5 Closed Loop TF



Z5 Disturbance Rejection



- Measurements are in **good agreement** with design values.
- Measurements **meet *(the sprit of)* their requirements**, as summarized in next page.
- Only Z5 is tested for ZCL. (Z6-Z11 are not tested)

Summary of FCL/ZCL Frequency Analysis

Metric	Requirement	Z4 Design	Z4 Measured	Z5-Z11 Design	Z5-Z11 Measured
Disturbance rejection bandwidth (Hz)	0.0016	0.0013	0.0013	0.0016	0.0014
Gain margin (dB)	> 6	14	13.8	9.5	9.5
Phase margin (degrees)	> 30	75	69	46	43
Delay (sec)	< 20	20	20	14.33	15.5

- External Schroeder input tests are used for analysis.
- Only Z5 is tested for ZCL. (Z6-Z11 are not tested)

- **Measurements are in good agreement with Design values.**
- **The disturbance rejection bandwidth does not meet the requirement in strict sense. However, it meets *the sprit of* the requirement, i.e., the lower frequency rejection is most important.**

Summary

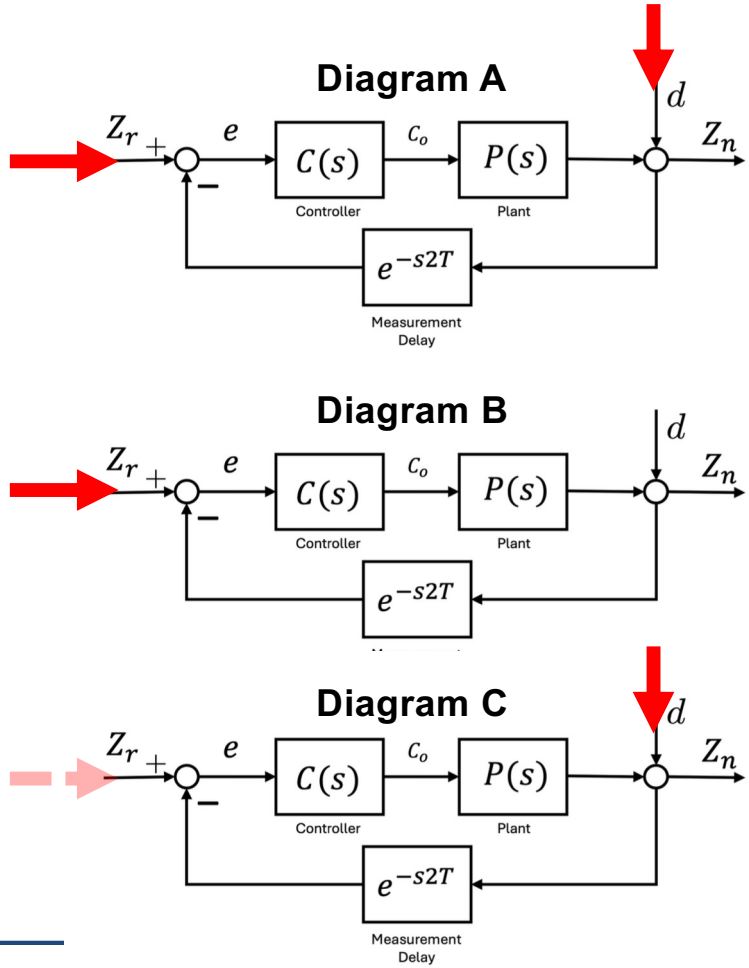
- FCL & ZCL work as designed/required for external perturbation.
- LOWFSC Zernike sensing errors are smaller than its requirement of 75 pm RMS.
- LOWFSC controls work better than 20 pm.
- Measure Zernike drift of ~ 10s of picometers over 5 hours dominated by Z6, Z9, and Z11.
- Measure contrast drift rate of 2E-9 over 5 hours.
- Desired (not required) but missing tests.
  - FCL/ZCL test with true external perturbation.
  - HOWFSC operation with all LCL, FCL, and ZCL closed. This further confirms the stability of the CGI control loop.
  - Follow-up test to identify the source of 2E-9 over 5 hours drift during OS10 trajectory test.
- More detail stories will be documented in the CGI JATIS paper 2024.

Back-up charts

Perturbation Injection

- Injection of Internal Perturbation
  - Use DM1 (Diagram A)
  - NOTE: DM2 internal perturbation test has not been tested.

- Injection of External Perturbation
  - No external stimuli (d) is available. Alternative approaches needed.
  - Instead of disturbance (d), we perturb the Zernike set points (*Zr*) for frequency response characterization. (Diagram B)
  - For OS10 trajectory demonstration, use following step to mimic the external perturbation. (Diagram C)
    - Record current *Zr*
    - Apply expected external WF change to DM1.
    - Restore *Zr*
  - NOTE: We chose DM1 to inject the perturbation over DM2 to avoid unnecessary complication raised by the DM1/DM2 inconsistency issue.



Test Calendar

	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	30-Mar	31-Mar	1-Apr	2-Apr	3-Apr	4-Apr	5-Apr	6-Apr
Day	N/A	• HOWFSC (TV-30)	• HOWFSC (TV-30)	• Dim the star (Vmag 3) • Initial Acquisition and alignment (TV-34) • HOWFSC per OADD (TV-35)	• Restore to bright star (Vmag 0) & LOWFSC Sensor calibration • **Focus Control Loop Test (TV-38)**	• Spectroscopy Wavelength Calibration (TV-40b) • **Photometry calibration information lost + System upset**	• TV-41:Finish TV-40b (Spectroscopy Wavecal) & PAM Alignment • In Parallel: Hold Hot Thermal Balance Data Review Pt. II	• **Complete Zernike Control Loop Test (TV-39)** • PBAT to complete TV-13b: PID Thermal Control (Closed Loop) to address PFR 218336
Swing	N/A	• HOWFSC (TV-30)	• HOWFSC (TV-30)	• HOWFSC per OADD (TV-35)	• Take additional images to address PFR 218555 (3-5:30pm) • Update and configure FSW V 1.1.3. (start 5:30pm) • Simultaneously at 5:30pm: CC Take QCM water measurement (Annex)	• **Focus Control Loop Test (TV-38)** • Start TV-22: Phase Retrival with DM at 0V and OTA maps	• **Zernike Control Loop Test (TV-39)**	• Transition to Cold Thermal Balance Simultaneously: CC Take QCM Measurements (Annex)
Grave	• **LOWFSC Sensor Trained with initial HOWFSC Solution with bright star (Vmag 0)** • HOWFSC (TV-30)	• HOWFSC (TV-30)	• HOWFSC (TV-30) • **NFOV Band 1 Dark hole generated** (HOWFSC ID 250)	• Observation per OADD (TV-36) • Core Throughput Measurement (TV-37)	• Spectroscopy PAM Alignment (TV-40a)	• Complete TV-22: Phase Retrival with DM at 0V and OTA maps • TV-37: Core Throughput Measurement • Diagnostic PBAT (potentially TV-39)	• **Zernike Control Loop Test (TV-39)**	• Transition to Cold Thermal Balance

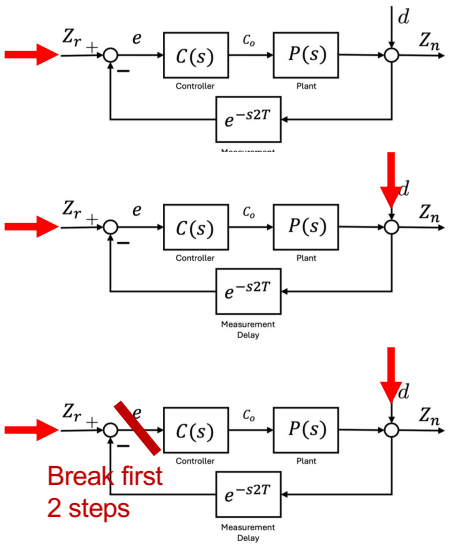
Step Response Expected

- For the quicker and fast convergence, CGI FSW employs **2-Step OFF scheme** for the internal perturbation.
  - NOTE: **No Requirement** on convergence speed for the internal perturbation.

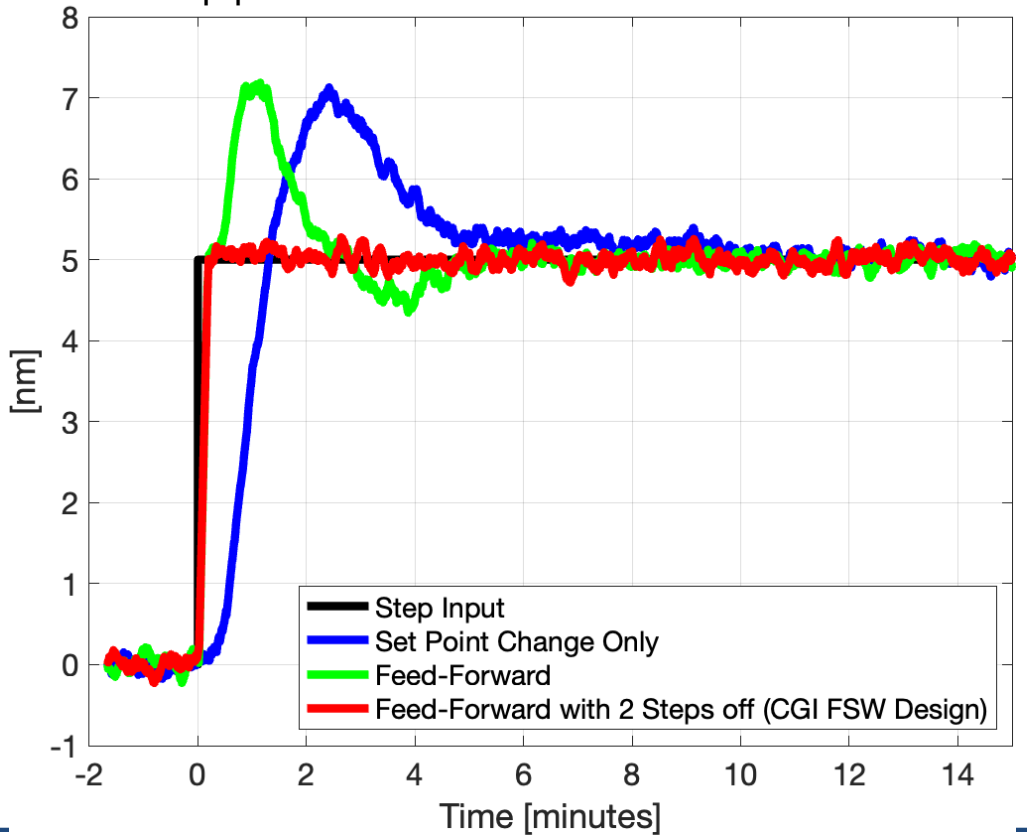
Set Point Change only

Feed-Forward

Feed-Forward with 2 Step OFF

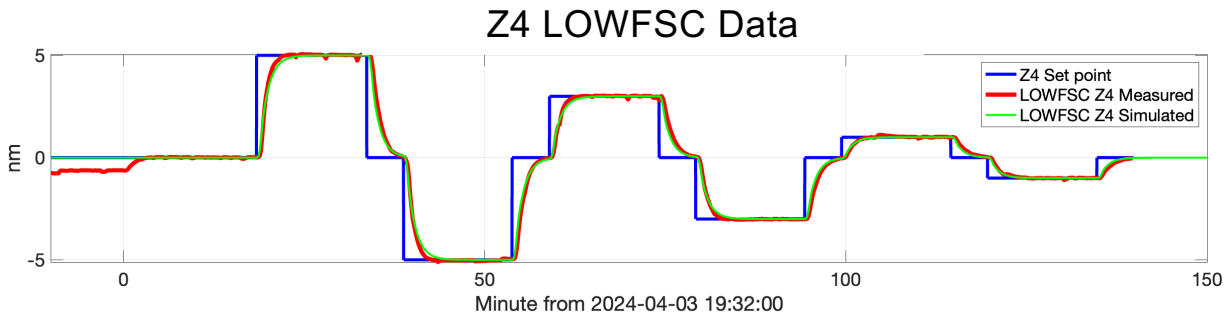


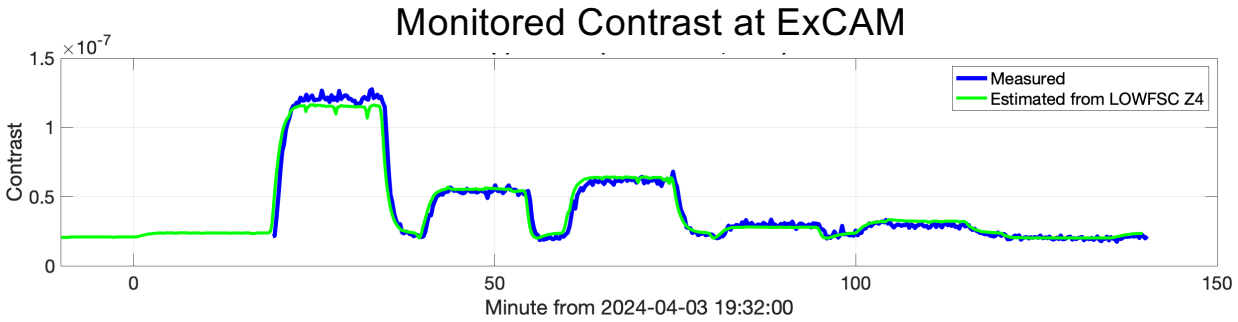
Expected LOWFSC Z5 – Z11 Measurement for Step perturbation



FCL Test for External Step Input

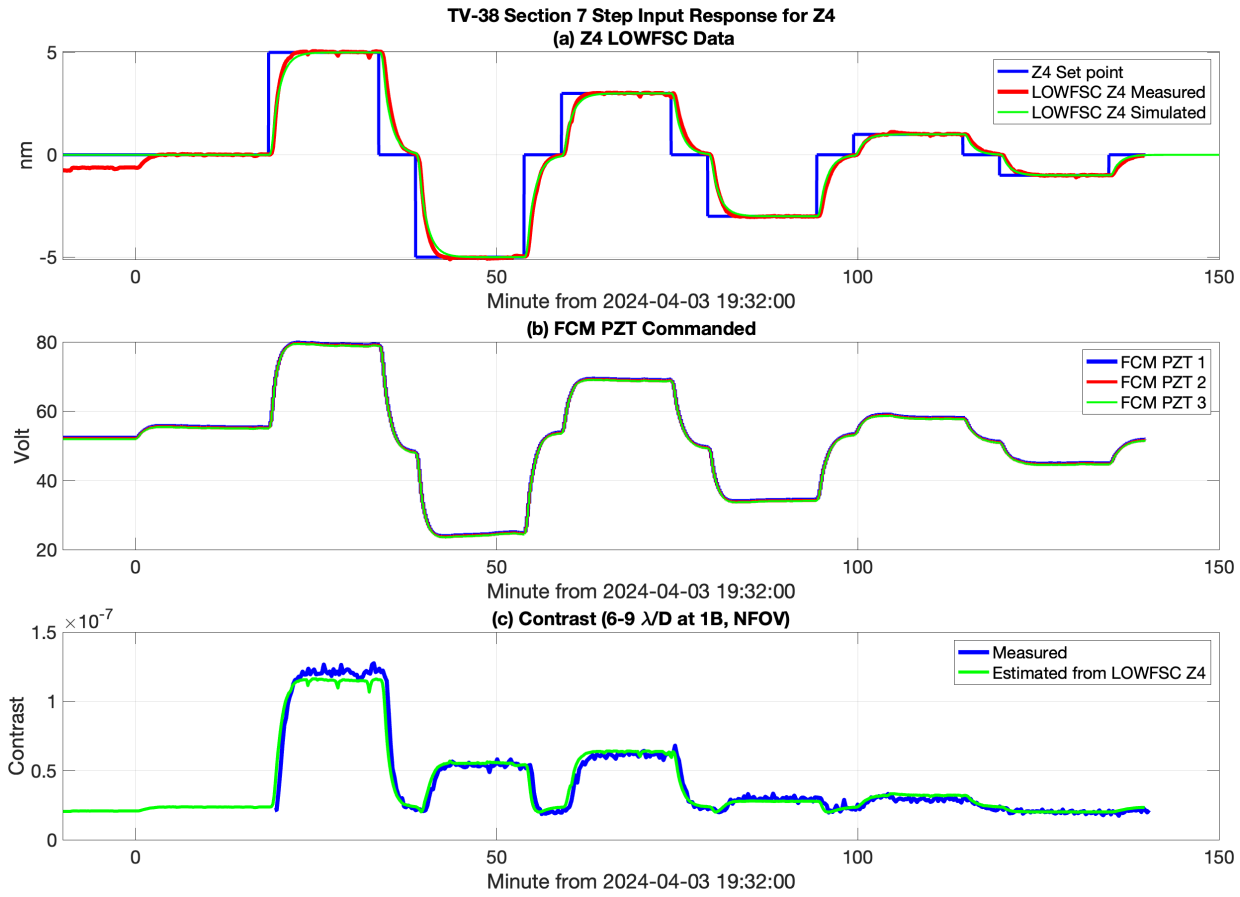
- Test Objective
  - Verify FCL works as expected by model.
- Test Setup
  - With no available stimuli, inject Z4 set points.
  - $\pm$ 5, 3, 1 nm Steps
  - 15 minutes long injection while control bandwidth is 1.6 mHz (or ~10 minutes)
- The measured LOWFSC Z4 is in **good agreement** with model simulation.
- Concurrent Contrast measurement
  - Contrast sensitivity of > 2.44E-9 /nm^2 to Z4 is measured.
  - Z4 bias of -1.22 nm is measured in the dark hole. (Some of its cause unknown)





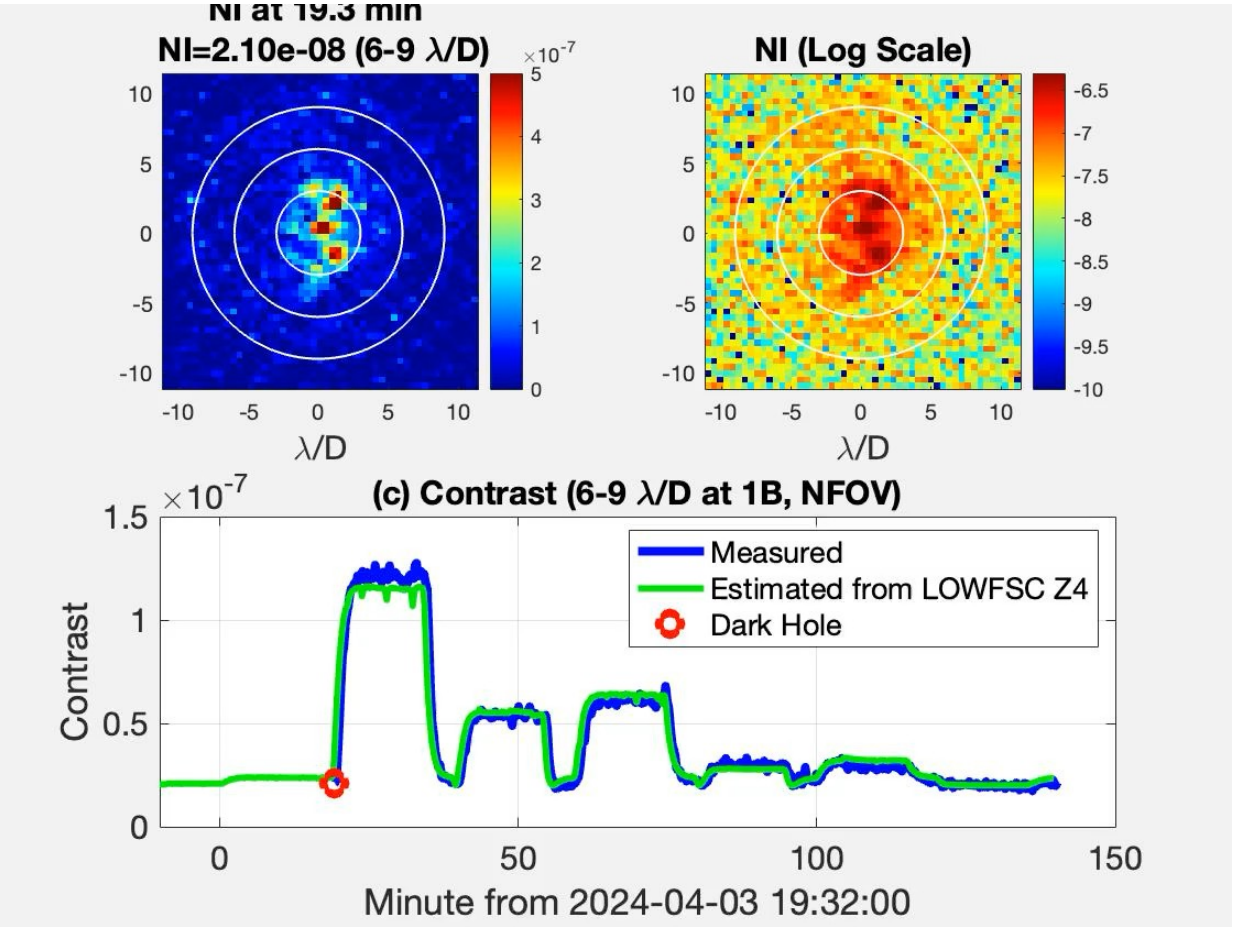
Test 1: FCL Test for External Step Input …

- Test Objective
  - Verify FCL works as expected by model.
- Test Setup
  - With no available stimuli, inject Z4 set points.
  - ± 5, 3, 1 nm Steps
  - 15 minutes long injection while control bandwidth is 1.6 mHz (or ~10 minutes)
- The measured LOWFSC Z4 is in **good agreement** with model simulation.



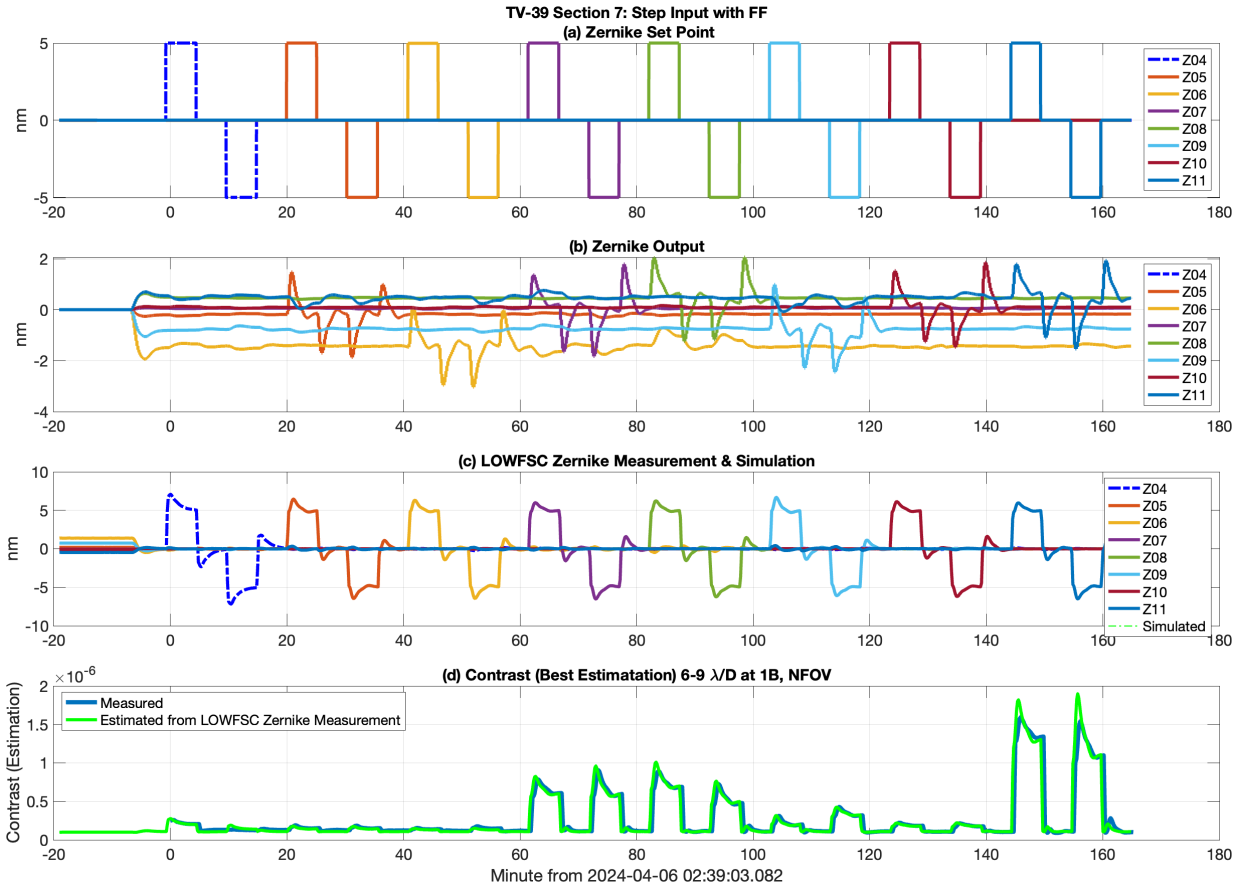
… Test 1: FCL Test for External Step Input

- NFOV Band 1 dark hole was monitored concurrently.
- Observe the Contrast upset when Z4 $\pm$ 5 nm is applied.
- Contrast sensitivity of > 2.44E-9 /nm^2 to Z4 is measured.
- Z4 bias of -1.22 nm is measured in the dark hole. (Some of its cause unknown)



Test 3: FCL/ZCL Test for Internal Step Input …

- Test Objective
  - Verify ZCL works as expected by model for internal perturbation.
- Test Setup
  - Apply Z4-Z11 each by applying DM1 template 5 nm.
  - ± 5 nm Steps
  - 5 minutes long injection with Feed-Forward
- The measured LOWFSC Z4-Z11 are **NOT agreeing** with 2-Step OFF scheme but in good agreement with the case with no extra step off (Under investigation) (Plot will be updated)

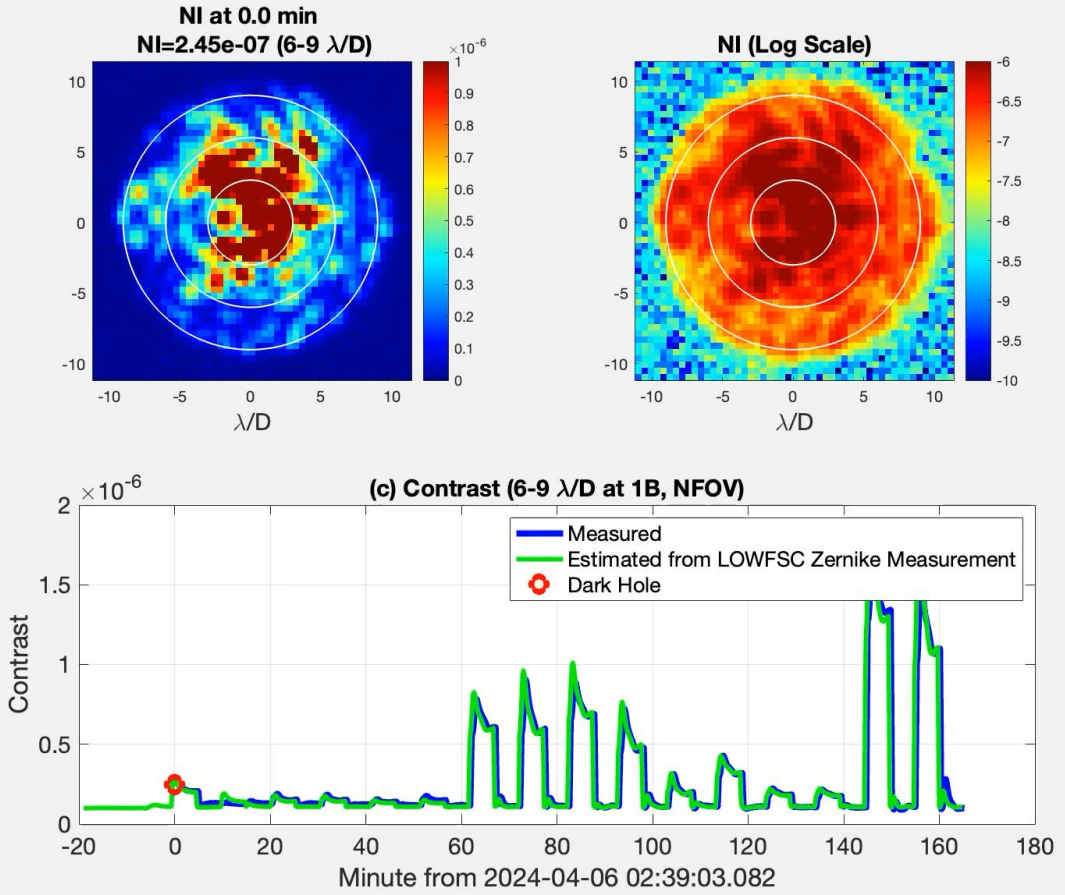


… Test 3: FCL/ZCL Test for Internal Step Input

- EXCAM images are saturated unintentionally for Test 3. We cannot quantify the contrast sensitivity on each Zernike correctly.
- Nonetheless, we evaluate the lower bound of Zernike sensitivity.

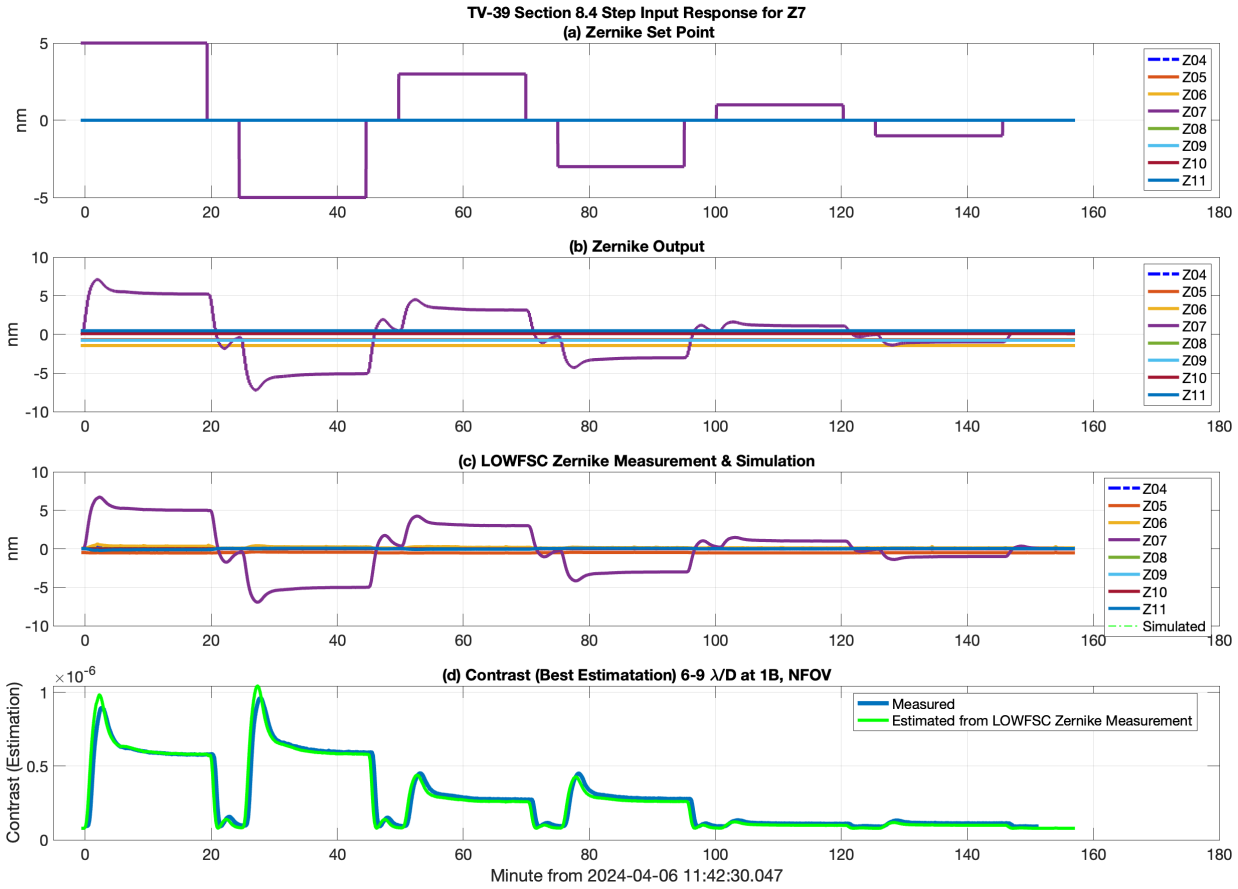
Measured lower bound of Zernike Sensitivity

Per nm²	Measured in Test 3	Model
Z4	2.44e-9	3.71e-9
Z5	>1.5e-9	6.64e-10
Z6	>1.0e-9	1.07e-9
Z7	>2.0e-8	2.2e-8
Z8	>2.0e-8	1.99e-8
Z9	>6.3e-9	8.67e-9
Z10	>3.0e-9	3.44e-9
Z11	>4.5e-8	4.96e-8



Test 4: ZCL (Z7) Test for External Step Input …

- Test Objective
  - Verify ZCL works as expected by model.
- Test Setup
  - Same as Test 1 except Z7 test with ZCL closed.
- The measured LOWFSC Z7 is in **good agreement** with model simulation. (To be updated)



… Test 4: ZCL (Z7) Test for External Step Input

- EXCAM images are saturated unintentionally for Test 4. We cannot quantify the contrast sensitivity on each Zernike.
- Contrast sensitivity of > 4.5E-9 /nm^2 to Z7 is measured. (> is for accounting for EXCAM saturation)
- Not like Z4, No Z7 bias offset is observed