Sensitivity of WFIRST Coronagraph Broadband Contrast Performance to DM Actuator Errors

Erkin Sidick

Byoung-Joon Seo, Brian Kern, Ilya Poberezhskiy, Bijan Nemati, and John T. Trauger

Jet Propulsion Laboratory
California Institute of Technology

Outline

- Summary of previous work: Effects of Xinetics DM errors on coronagraph contrast performance
- Effects of actuator constraints and a DM defect on HLC contrast
- Effects of actuator gain calibration errors on HLC contrast
- Effects of actuator gain calibration errors on contrast sensitivity to Zernike-mode WFE
- Comparison of model with testbed: Contrast floor and contrast chromaticity
- Summary

Summary of Previous Work

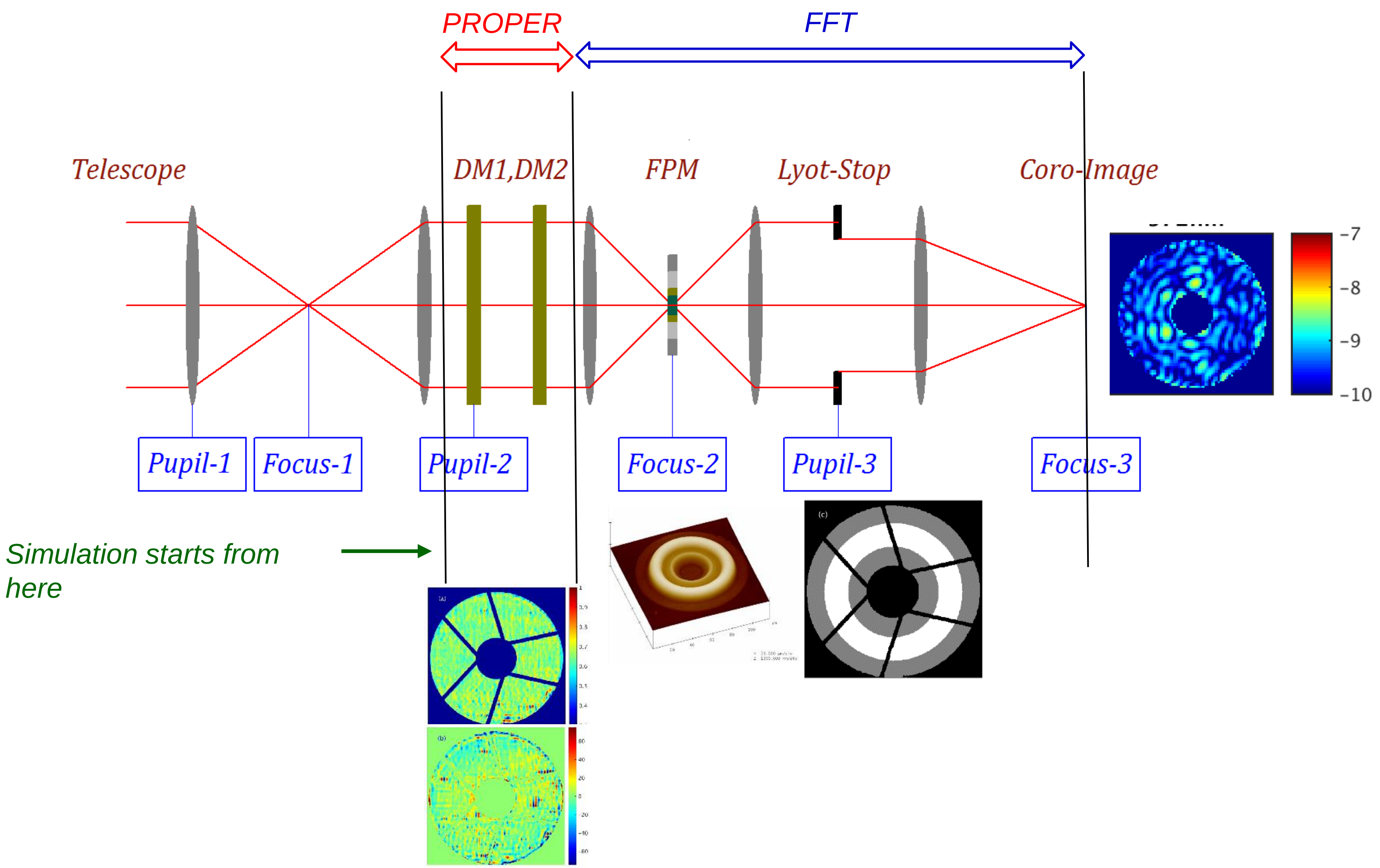
- *On effects of Northrop Grumman Xinetics DM errors on coronagraph performance*
- *E. Sidick is the first author for these papers*

Year/Paper #	Coronagraph	Main Topics
2010 (SPIE-7731)	HCIT/PIAA	Random gain errors Asymmetric actuator response Nonlinearity of actuator response Dead actuators
2015 (SPIE-9605)	HCIT	1 - 4 pairs of pegged (frozen) actuators
2015 (SPIE-9605)	WFIRST/HLC	Effects of gain errors on LOWFS/C Effects of actuator command digitization errors on LOWFS/C
2016 (SPIE-9912)	WFIRST/HLC	Lateral and longitudinal translation of DM's Clocking of DM's Jacobian mismatch between model and testbed

Jet Propulsion Laboratory
California Institute of Technology

HLC Model of Simulation Code

- Includes key elements of HLC
- Same as that of Control Code
- Input pupil amplitude and phase maps are applied before DM1



Definition of "Baseline Model"

- Baseline model uses a set of pupil, DM1, DM2, Occulter and Lyot-Stop parameters obtained directly from the HLC testbed
- MC (Monte-Carlo) simulations will also be performed.
- MC1 is an example of MC errors generated randomly from the RMS values in the table

Name	Parameter	Symbol	Unit	Testbed Baseline	MC Error RMS	MC Error Case #1
Pupil	Pupil Diameter	D	pix	305.3		
DM1	X-Decenter	Tx	um	-94.1	50	-26.0
	Y-Decenter	Ty	um	-475.1	50	-35.9
	X-Rotation (Tip)	Rx	deg	8.25		
	Y-Rotation (Tilt)	Ry	deg	-0.07		
	Z-Rotation (Clocking)	Rz	deg	-0.86	0.05	-0.06
DM2	X-Decenter	Tx	um	799	50	-42.8
	Y-Decenter	Ty	um	-83.5	50	-45.9
	X-Rotation (Tip)	Rx	deg	2.37		
	Y-Rotation (Tilt)	Ry	deg	0.004		
	Z-Rotation (Clocking)	Rz	deg	0.45	0.05	0
Lyot	X-Decenter	Tx	um		25	34.2
	Y-Decenter	Ty	um		25	3.4
Occ	X-Decenter	Tx	um		0.5	-0.3
	Y-Decenter	Ty	um		0.5	0.4
Pupil Amplitude		Amp		Meas	Meas	Meas
Pupil Phase		Phase		Meas	Zern + PSD	Zern + PSD

Measured Maps and Actuator Constraints

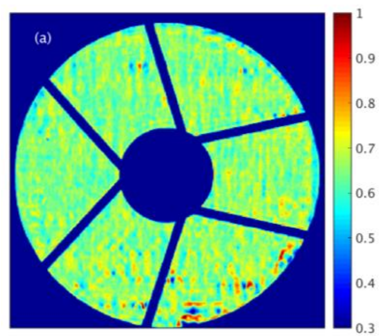
- Many similar maps were measured on the OMC (Occulting Mask Coronagraph) testbed
- Shown here is just one set of examples
- Use these measured pupil phase and amplitudes in the simulations of this paper

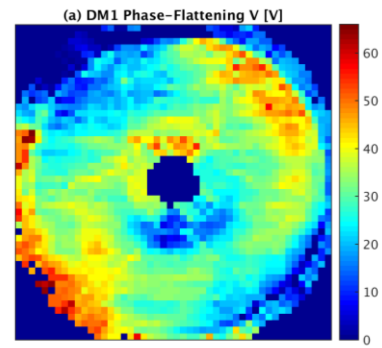
- DM actuator command constraints included:
  - Stroke limit (0 – 100V)
  - Neighboring rule (|ΔV| < 30V)
  - DM1 paired actuators (2 pairs)

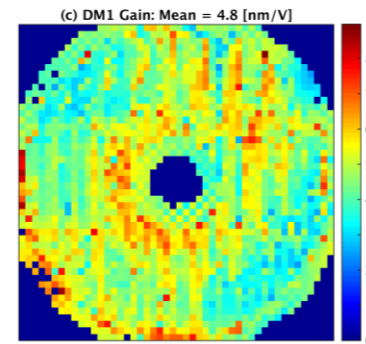
Flat-State DM Commands

DM Gains

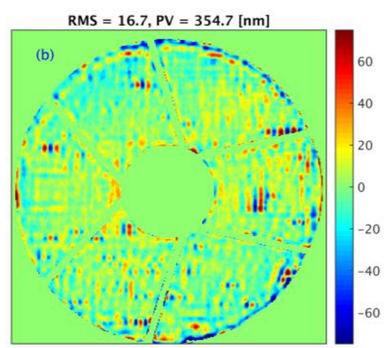
Pupil Amplitude

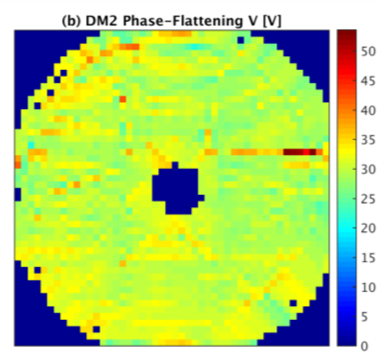


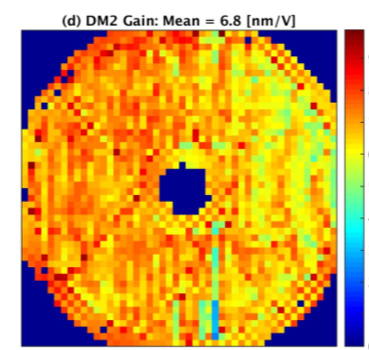




Pupil Phase





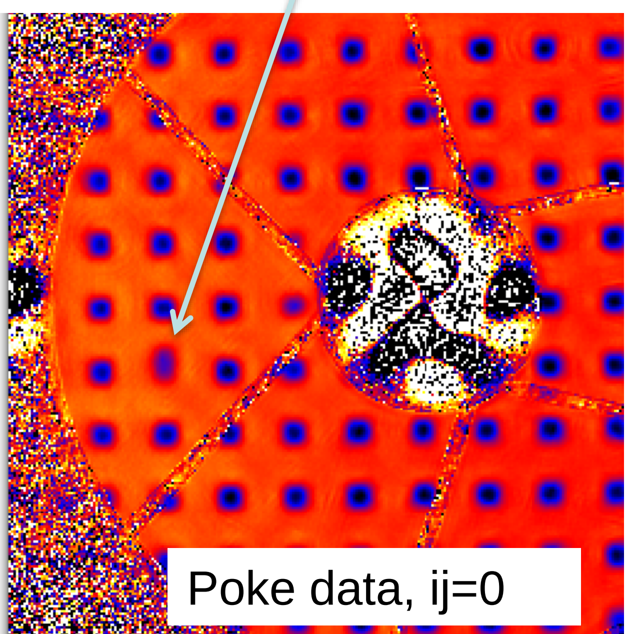


DM1 Paired Actuators

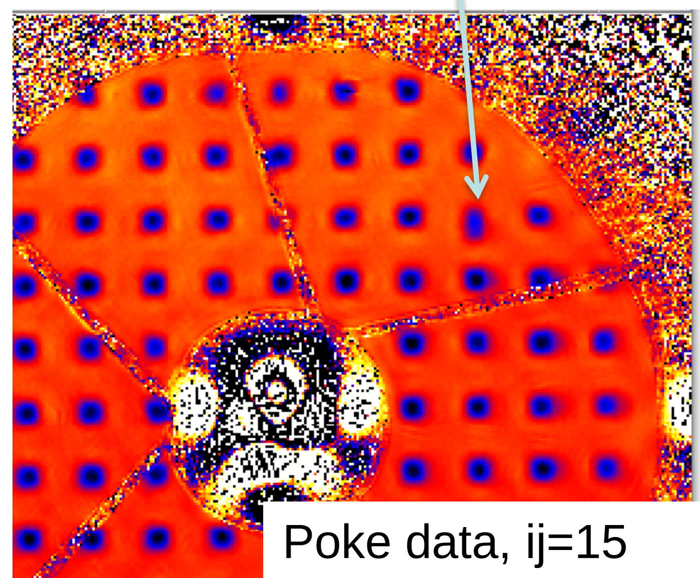
Courtesy of Byoung-Joon Seo

- NOTE :
  - 1st pair is already known from static HLC TB.
  - 2nd pair is new

1st pair : [y, x]= [40,27] & [40,28]



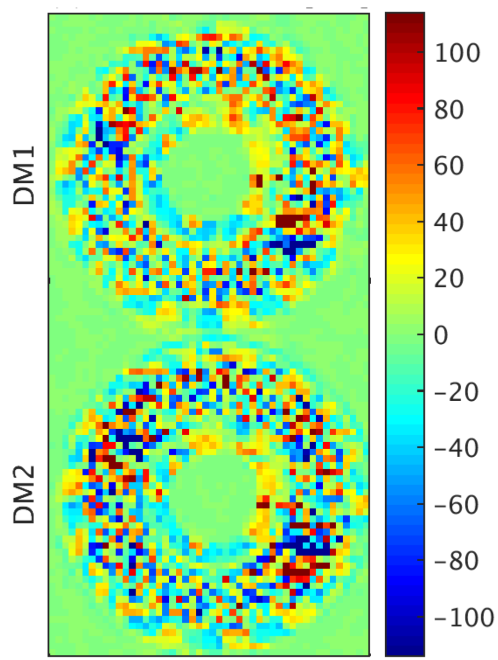
2nd pair : (NEW) [y, x] = [11,11] & [11,12])



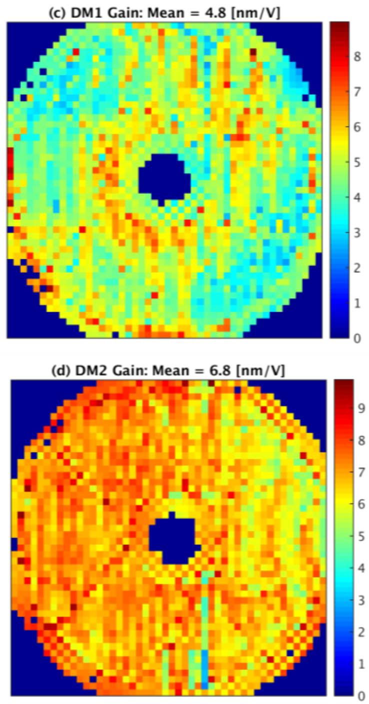
How to Apply Act Stroke Limits?

- Obtain dark-hole actuator heights Δh in nm
- Divide Δh by actuator gain maps to convert nm into V to obtain ΔV
- Add ΔV to Phase-Flattening commands
- Check for command limits and neighboring-rule, and fix any problems
- Pair the two-pairs of actuators in DM1 (with the mean command value)

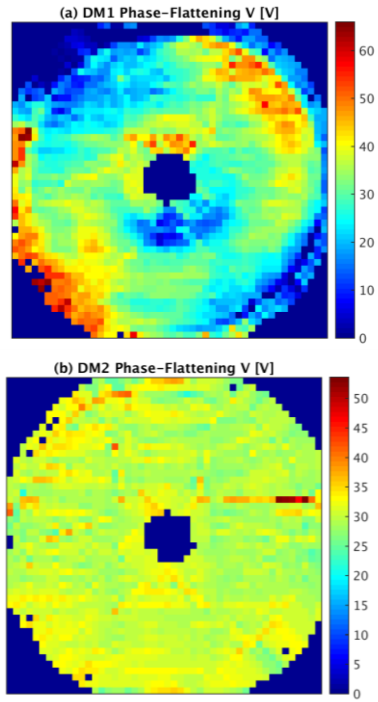
Act Heights in nm



DM Gains

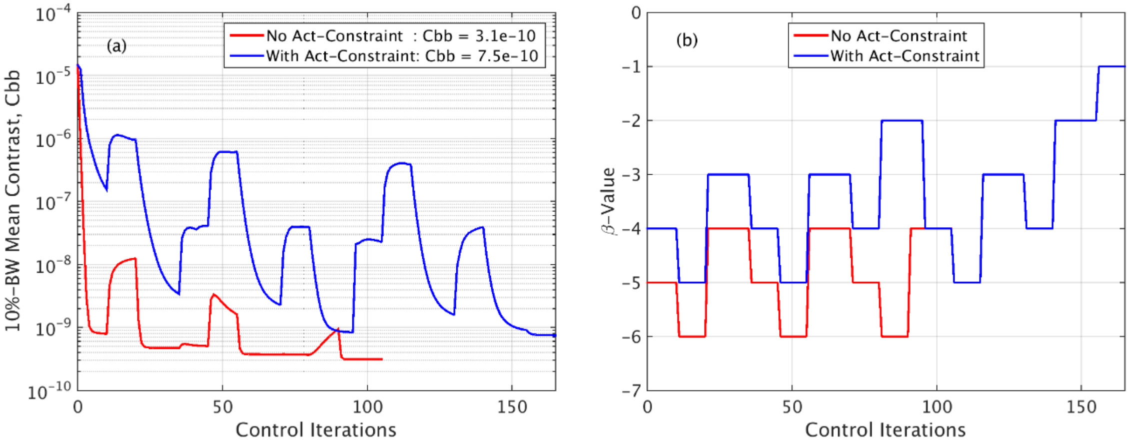


Phase-Flattening Commands

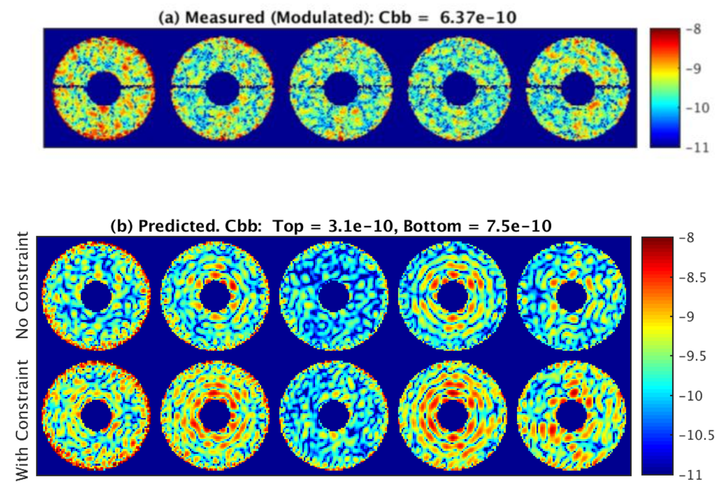


EFC with & without Act Constraints

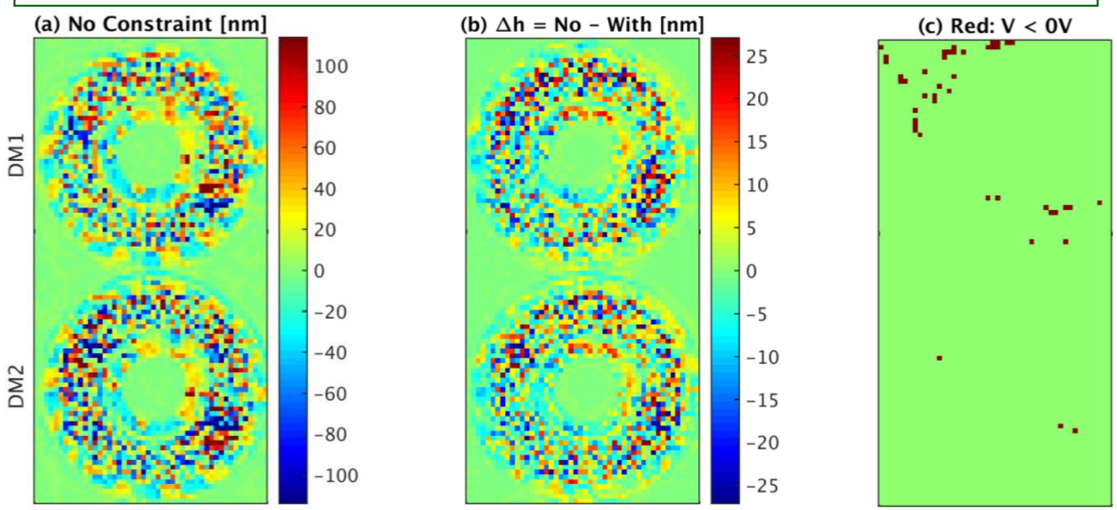
- Actuator constraint degrades 10%-BW mean contrast C_{bb} by > 2x
- When no actuator constraint is included, commands of some actuator become < 0V, but no actuator with > 100V in this case
- New β-schedule is used—See Paper #10400-74 (Poster session tomorrow)



Normalized Intensity Maps
528 531 550 561 572nm



Actuator Heights needed to produce dark-hole

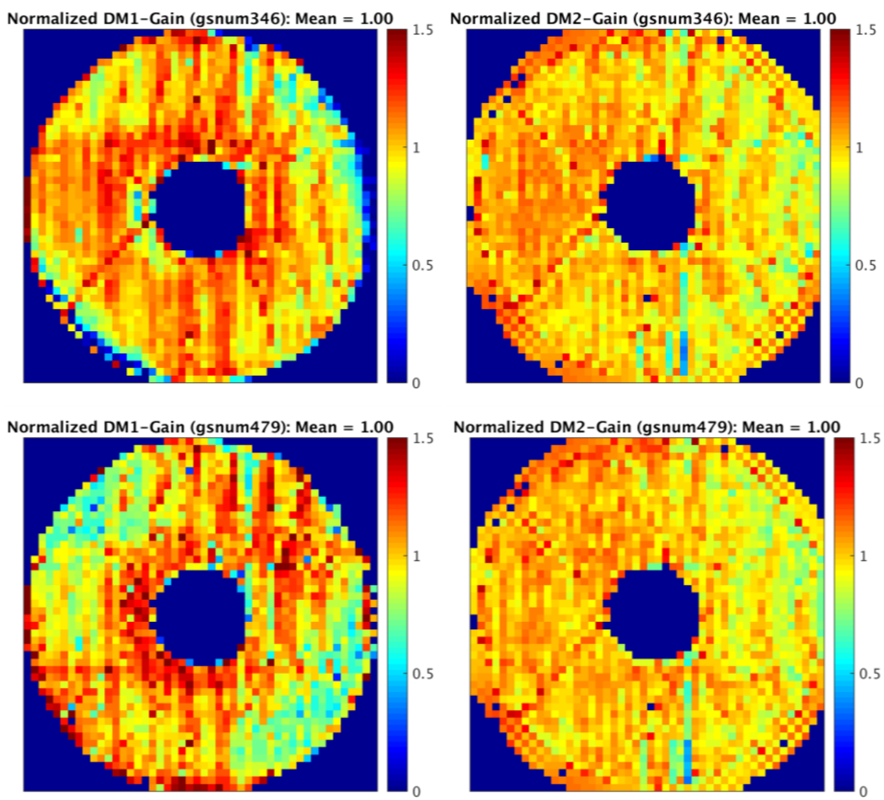


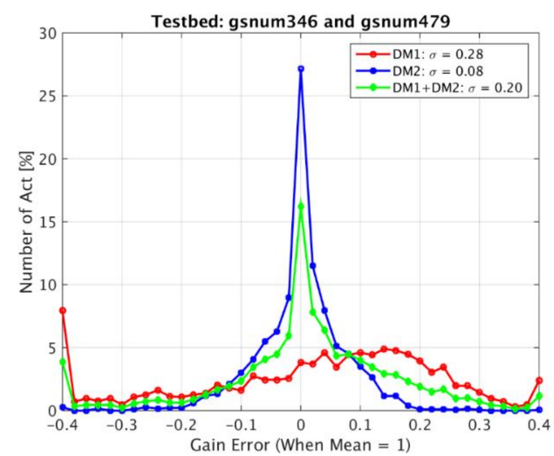
DM Actuator Gain Errors: Two Examples (TB Run346 & 479)

- Shown below are 2 sets of measured (normalized) act gain maps
- Plot on right shows an estimate of DM actuator gain errors obtained from this pair of gain maps
- B. J. Seo analyzed more than 5 sets of similar measurement data, and the results are comparable
- Will assume gain errors with $\sigma = 0.20$ (normal - distribution)

First Pair (measure on 6/26/2016)

Second Pair (measured on 9/2/2016)





Jet Propulsion Laboratory
California Institute of Technology

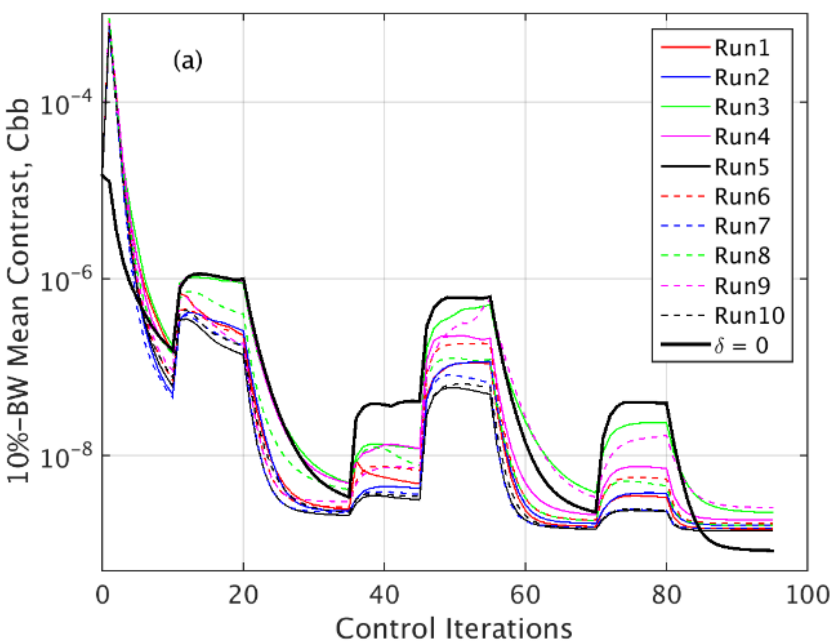
Effects of DM Actuator Gain Errors: Results of 10 Runs of Monte-Carlo Simulations

- Includes actuator constraint
- Gain errors are fixed during each EFC session
- Gain errors with σ = 0.20 degrade C_{bb} by ~2x

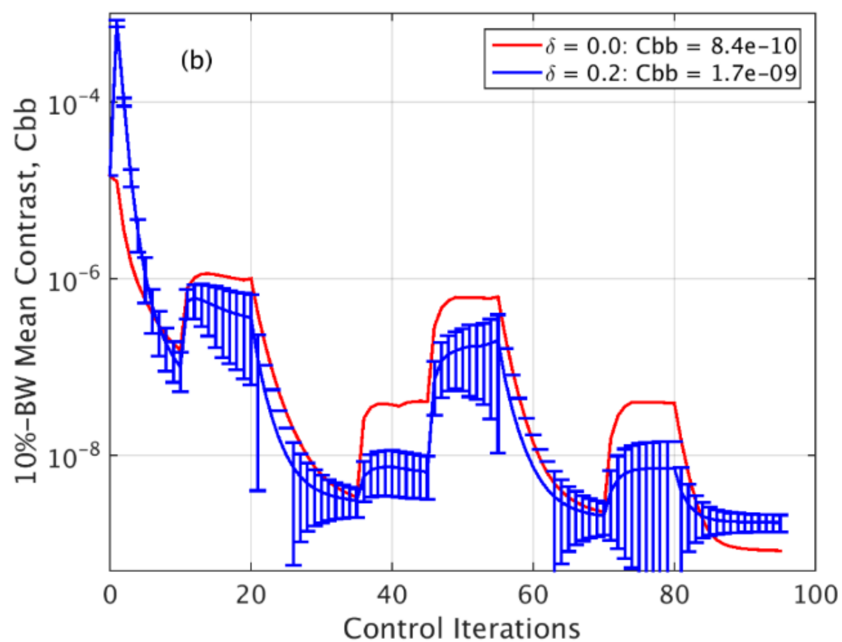
$$\Delta h_i(\delta) = \Delta h \times \left[1 + \delta \times randn(i)\right]$$

$$randn = \text{Random} - \text{number generator (normal} - \text{distribution)}$$

Results of Individual MC Runs



Mean, Error-Bar, and Comparison with Nominal



Effects of Act Gain Errors on Contrast Sensitivity to Zernike-Mode WFE

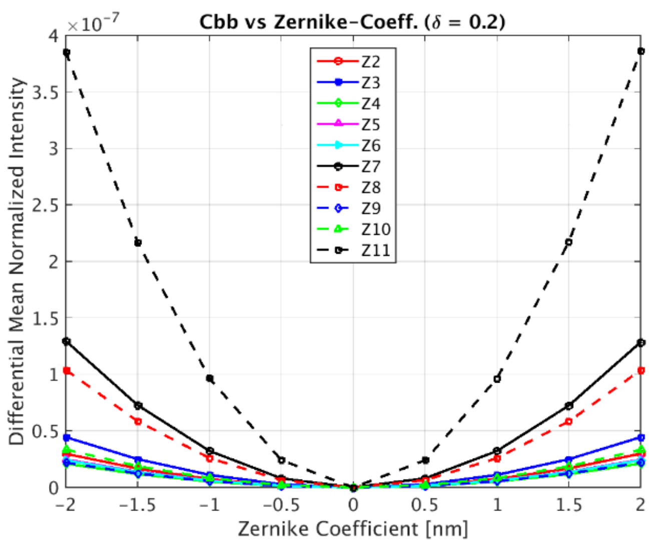
- Measurement is part of the dynamic tests
- Measurement and simulates are performed in the following steps:
  - Obtain a contrast floor of C_{bb} ~ 10^{-9} (modulated component for testbed)
  - Dial-in Zernike-modes Z_2 – Z_{11} by commanding DM2 actuators accordingly, one mode at a time, and vary Zernike-coefficient value, Z_i, in the [-2 2] nm range with an increment of 0.5nm
  - Record the open-loop values of the mean normalized intensity, I_n
  - Fit second-order polynomial to I_n vs Z_i in the form of

$$I_n(Z_i) = a_2 Z_i^2 + a_1 Z_i + a_0$$

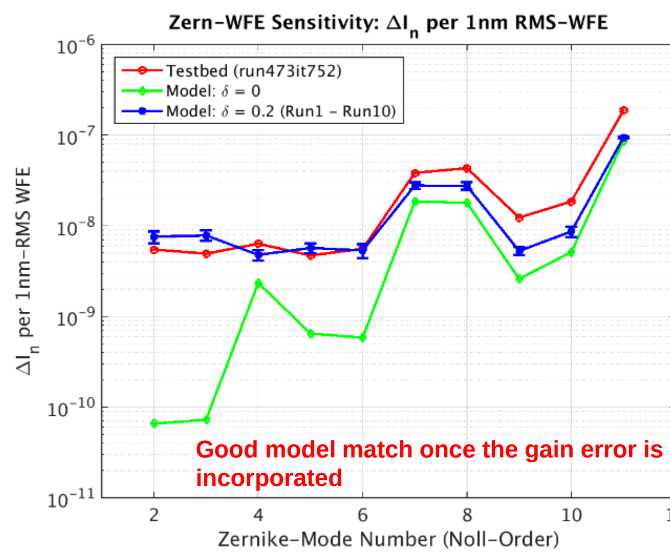
  - Plot a_2 as a function of Zernike-mode number (Noll-order)

- Act gains errors with δ = 0.20 greatly improve the agreement between prediction and measurement, especially for Z2 – Z6

Mean Normalized Intensity vs Zernike Coef



Mean Contrast Sensitivity to Zernike-Mode WFE
(Simulation: Results of 10 Monte-Carlo Runs)



Contrast Floor and Chromaticity: 10 Sets of Monte-Carlo Errors to be Used

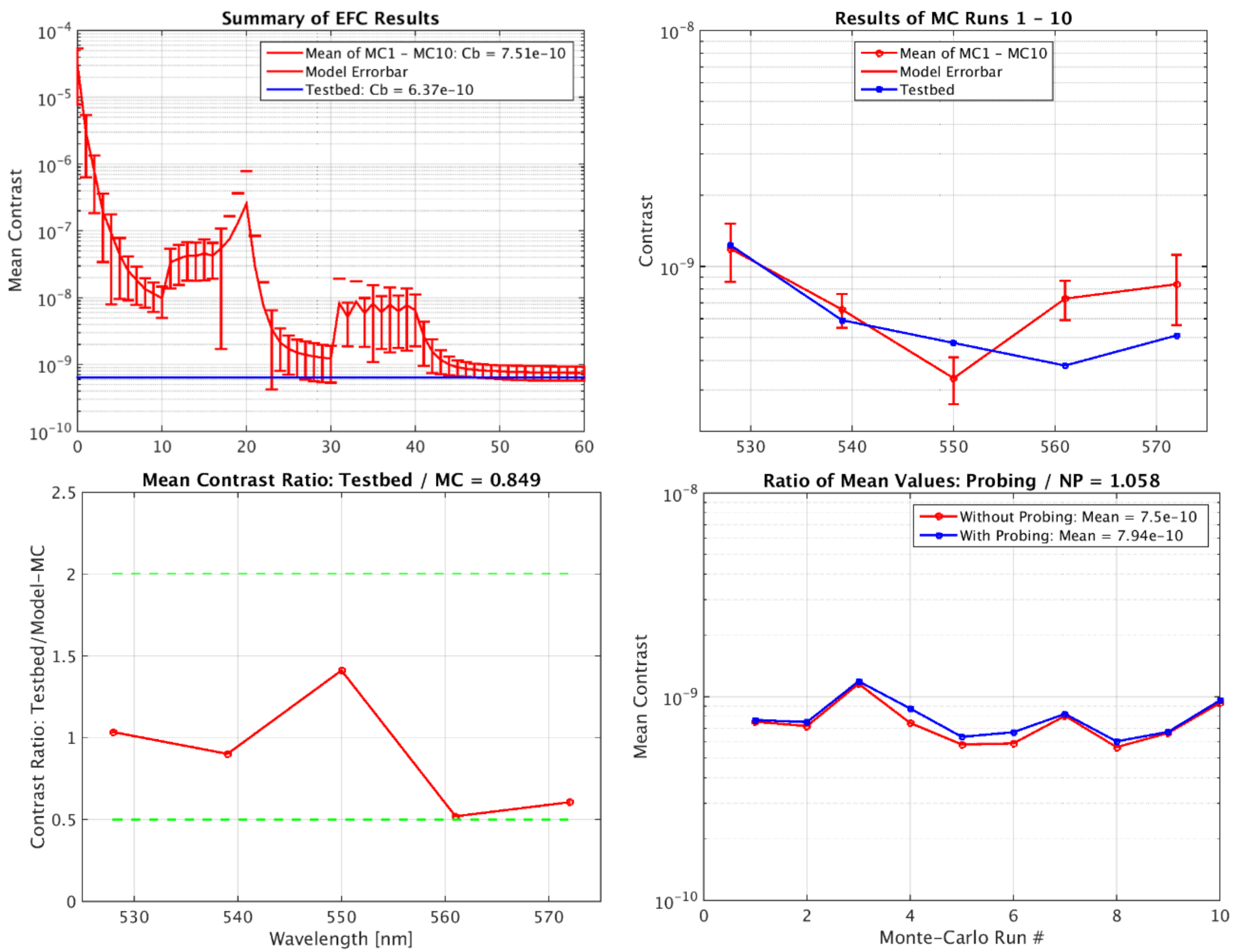
- Used pupil amplitudes measured at different times
- From a pair of measured pupil phase maps, obtained Zernike-coefficients and PSD parameters
- Randomly generated differential phase errors from the above parameters
- Added the random differential phase to nominal one for different MC runs
- Other errors are randomly generated using the MC error RMS values (smaller table below)

	DM1			DM2			Occ		Lyot		Amplitude	Phase
MC-#	Tx	Ty	Rz	Tx	Ty	Rz	Tx	Ty	Tx	Ty		
1	-26	-35.9	-0.06	-42.8	-45.9	0	-0.3	0.4	34.2	3.4	Meas-1	Meas0 + Synthesized-1
2	20.1	58.5	-0.02	19.5	10.7	-0.04	-0.2	-0.3	-18.6	-29.5	Meas-2	Meas0 + Synthesized-2
3	-4.2	-47.3	-0.01	-26.7	62.7	-0.04	0.7	-0.1	-5.1	13.6	Meas-3	Meas0 + Synthesized-3
4	-65.6	47.1	-0.02	50.3	-15.6	0	-0.3	0	-17.3	-19.7	Meas-4	Meas0 + Synthesized-4
5	-57.5	-12.1	-0.06	6.4	21.6	0.06	0.7	-0.3	2.1	8.6	Meas-5	Meas0 + Synthesized-5
6	-37.5	16.1	0.04	62.4	-2.1	0.02	0.1	-0.7	20.2	3.3	Meas-6	Meas0 + Synthesized-6
7	39.4	68.4	-0.04	-5.9	-13.1	-0.01	0.3	-0.3	14	19.2	Meas-7	Meas0 + Synthesized-7
8	-2.8	58.6	-0.03	-54.5	-4.8	-0.01	0.3	-0.6	12.1	-32.8	Meas-8	Meas0 + Synthesized-8
9	-3.4	36.2	0	4.7	58.7	-0.01	0.1	0.7	-21.4	24.1	Meas-9	Meas0 + Synthesized-9
10	48	-62.5	-0.06	55.2	67.7	0.02	0.7	0	-3	4.2	Meas-10	Meas0 + Synthesized-10
Unit	um	um	deg	um	um	deg	um	um	um	um		

Name	Parameter	Symbol	Unit	Testbed Baseline	MC Error RMS	MC Error Case #1
Pupil	Pupil Diameter	D	pix	305.3		
DM1	X-Decenter	Tx	um	-94.1	50	-26.0
	Y-Decenter	Ty	um	-475.1	50	-35.9
	X-Rotation (Tip)	Rx	deg	8.25		
	Y-Rotation (Tilt)	Ry	deg	-0.07		
	Z-Rotation (Clocking)	Rz	deg	-0.86	0.05	-0.06
DM2	X-Decenter	Tx	um	799	50	-42.8
	Y-Decenter	Ty	um	-83.5	50	-45.9
	X-Rotation (Tip)	Rx	deg	2.37		
	Y-Rotation (Tilt)	Ry	deg	0.004		
	Z-Rotation (Clocking)	Rz	deg	0.45	0.05	0
Lyot	X-Decenter	Tx	um		25	34.2
	Y-Decenter	Ty	um		25	3.4
Occ	X-Decenter	Tx	um		0.5	-0.3
	Y-Decenter	Ty	um		0.5	0.4
Pupil Amplitude		Amp		Meas	Meas	Meas
Pupil Phase		Phase		Meas	Zern + PSD	Zern + PSD

Contrast Floor and Chromaticity: Prediction vs Measured

- Simulation: Results of 10 Monte-Carlo error realizations
- Predicted contrast floor and contrast chromaticity agree with measurement within a factor of 2
- All simulation results of this study were obtained without using probing (e-field estimation)
- The effect of probing on contrast value is very small



Summary

- Investigated the effects of DM actuator constraints, actuator defects, and actuator gain calibration errors on EFC, HLC contrast floor, contrast chromaticity, and contrast sensitivity to Zernike-mode WFE
- It was shown that
  - Actuator constraint degrades BB mean contrast by more than 2x
  - Actuator gain errors degrade BB mean contrast by ~2x
  - Provides good model match once the act gain errors are included in Zernike WFE sensitivity simulations
- It was also shown through Monte-Carlo simulations that model prediction and testbed measurement on HLC contrast floor and chromaticity agree within a factor of 2