Jet Propulsion Laboratory
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Coronagraph

WFIRST

Wavefront Control Performance Modeling with WFIRST Shaped Pupil Coronagraph Testbed

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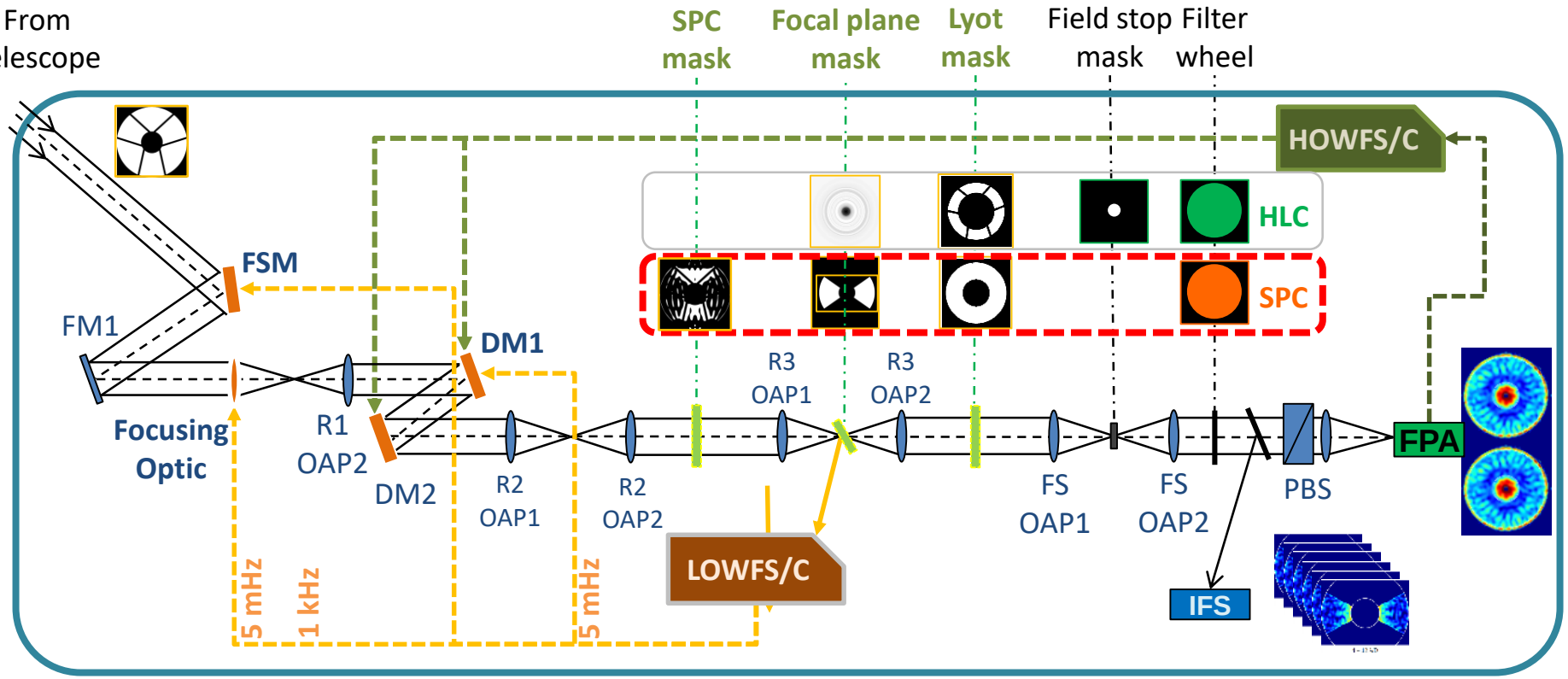
WFIRST Coronagraph Instrument (CGI)

Wide-**F**ield **I**nfrared **S**urvey **T**elescope - **C**orona**G**raph **I**nstrument

- Direct imaging and spectral characterize of both previously known and new exoplanets
- Consists of two CG types (HLC & SPC); two WFSC schemes (LOWFSC & HOWFSC); three focal plane detectors (imaging, LOWFS, and IFS)



Coronagraph Instrument

SPC: a set of 3 binary masks to reshape WFRIST obscured pupil diffraction into a high contrast dark hole

CGI Performance Modeling Need

- CGI Testbed Development Milestone 9: completed in January
  - Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light in a simulated dynamic environment*
  - *Testbed results must be consistent with model predictions* *- the focus of this talk*
    - *Do we understand the coronagraph operation well enough to predict its contrast performance?*

- Validate coronagraph model for the purposes of error budget, flight system design, flight system performance verification, etc.

** 10400-13, 10400-14, 10400-15, this conference Proc.*

CGI Modeling Challenge and Validation Focus

- Key performance metrics of coronagraph operation to CGI science goal (yield)
  - Speckle contrast (floor)
  - Efficiency (iteration) of dark hole digging (at low flux)
  - Robustness to contrast instability (sensitivity to disturbances)

- Testbed SPC model validation scope and focus:

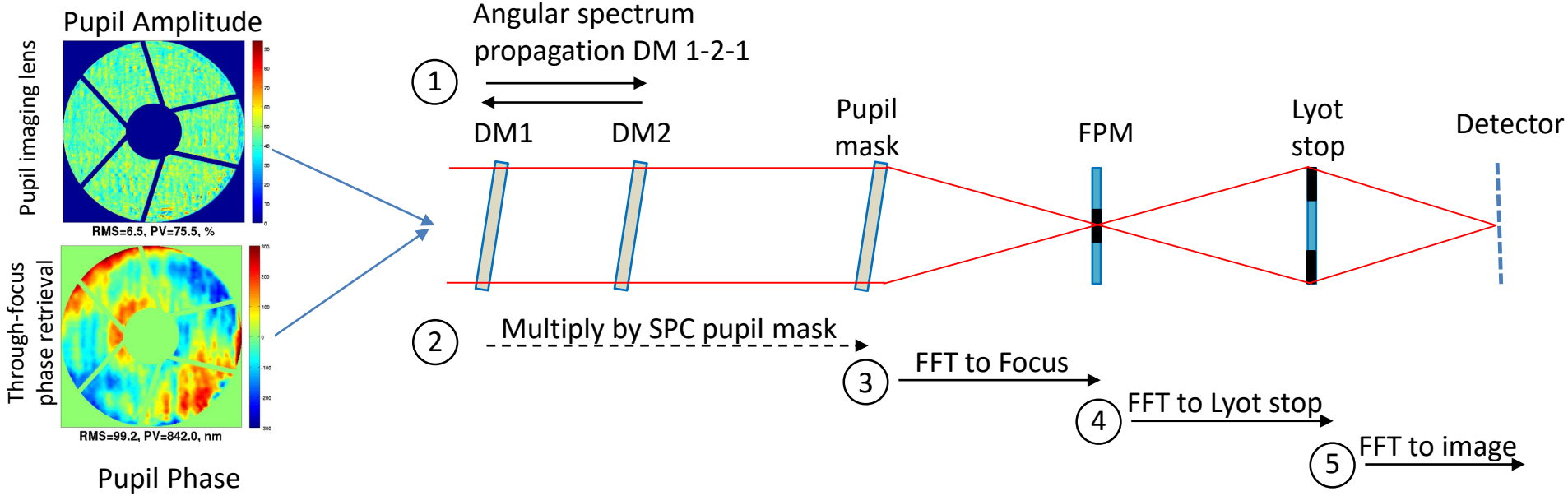
Modulated part of testbed (static) high-order WFSC performance & low order sensitivity

1) **Raw contrast performance - *contrast floor*, chromaticity & convergence rate** - main focus
   - Relative success on contrast sensitivity in the past but much less so on raw contrast*
   - Better fidelity in raw contrast ➔ better fidelity in contrast sensitivity
2) Contrast sensitivity - Low order Zernike WFE, mask lateral shear
   - Speckle stability direct affects science image quality /interpretation

* S. Shaklan. *et al., JPL TDEM Milestone 3a*: http://exoplanets.jpl.nasa.gov/exep/technology/TDEM-awards

Testbed WFSC SPC Modeling Approach

- Compact model (Fourier based except Fresnel between DM1 to DM2)
  - Driven by computation need; also the choice used in testbed control
  - Consolidated aberrations at pupil plane (except SP mask WFE at shaped pupil plane) in model
    - Phase Retrieval measured errors as they exist in system
- Electric Conjugation Field (EFC)* as WFSC choice



** Give'on, A., et al, Proc. SPIE. 6691, 66910A (2007); Proc. SPIE. 8151, 815110-2, (2011)*

Testbed WFSC SPC Modeling Approach - Cont'd

1. SPC baseline model w/ known imperfections /parameters $\{\tilde{p}_i\}$:
   - **Model includes many testbed nulling operation features**:
     - Low order DM flattening
     - High order EFC WFSC: probing (sensing) and DM control
       - Both sensing (pair-wised probing to get E field) and control (Jacobian) use parameters $\{\tilde{p}_i\}$
     - DM voltage constrains & neighborhood rule
     - Regular Jacobian updates
     - Testbed like EFC regularization control strategy
       - Fixed or alternating nominal & aggressive regularization
   - **Model includes known imperfections $\{\tilde{p}_i\}$ as measured**:
     - Pupil WFE and amplitude (achromatic initially; chromatic later)
     - SP mask WFE
     - DM and masks alignment (RB translation, clocking)
     - DM gains

(aka 'Control model' on testbed)

Testbed WFSC SPC Modeling Approach – Cont'd

2. SPC "Testbed" model w/ Monte Carlo knowledge errors $\{e_i\}$:

   A "Model" is used in both sensing and control parts on testbed:

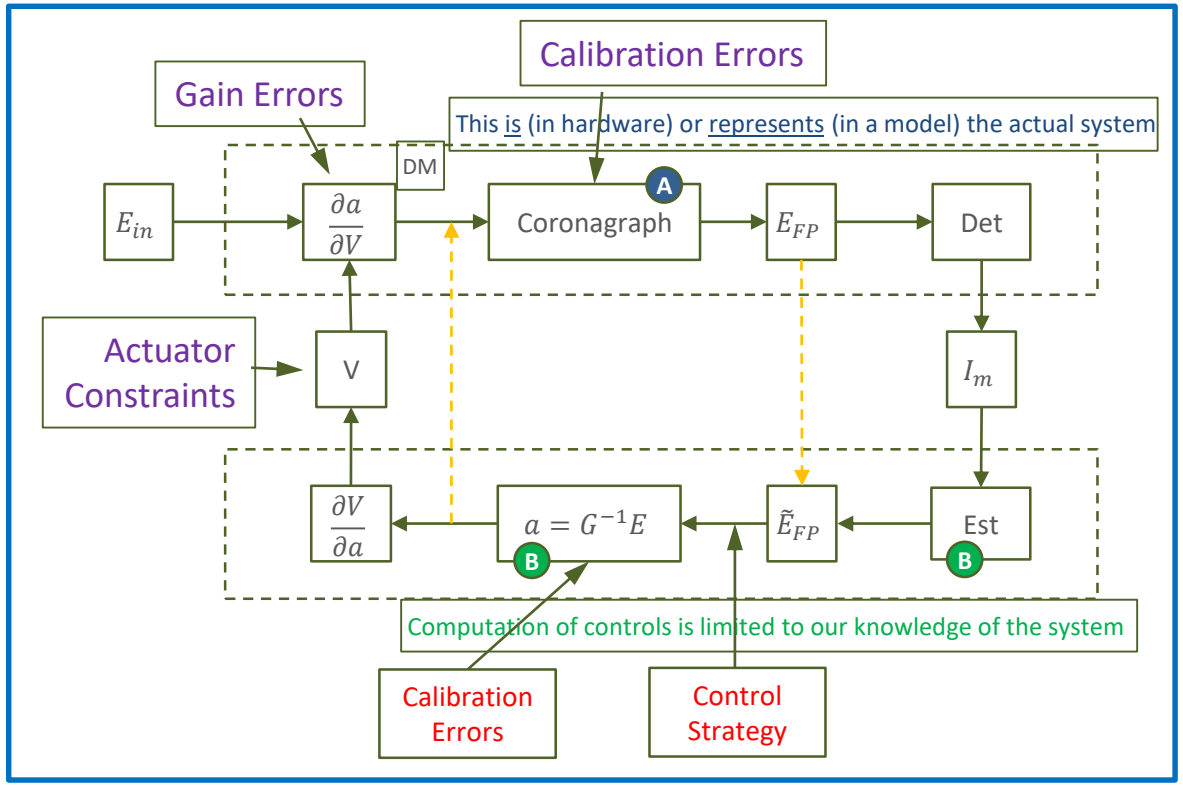
   – Use $\{\tilde{p}_i\}$ only *for Jacobian and probe only* E field calculation part during E estimation (B)

   – Use $\{p_i = \tilde{p}_i + e_i\}$ *for contrast evaluation and calculating of "measured" probing intensity* (probe+ aberrated field) during E estimation (A)

   – **Knowledge uncertainties include**:

   - Pupil WFE and amplitude (chromatic or achromatic)
   - SP mask WFE
   - DM aligment and gains
   - Masks (SPM, FPM, Lyot stop) alignment (RB translation, clocking)
   - SP mask manufacture
   - Occulter defocus
   - Source lateral shift

'Testbed model'



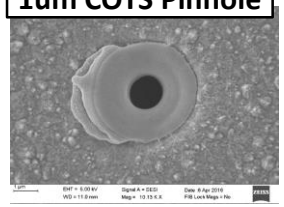
Testbed / Model Configurations Used

	Src generation	Src pinhole	Testbed EFC Ctrl strategy	Pupil WFE / amp in model(s)	note
Config.1	w/ OTA (dominant WFE)	COTS thick 1um dia	Mostly fixed regularization	Achromatic WFE; chromatic amp (Base model & part of MC runs)	Incomplete model
				* Chromatic WFE & amp; Estimated (later part of MC)	Imprecise data
Config.2	no OTA, long F# OAP	MDL thin 3um dia	Alternating regularizations	Chromatic; Measured (All models)	Better model and data

*Based on: 1) Polarization modeling estimates[+] 2) Testbed error budget analysis

[+] *D. Hoppe on pinhole and J. McGuire on MCB (before DM1); internal documents (JPL)*

Config.1
1um COTS Pinhole



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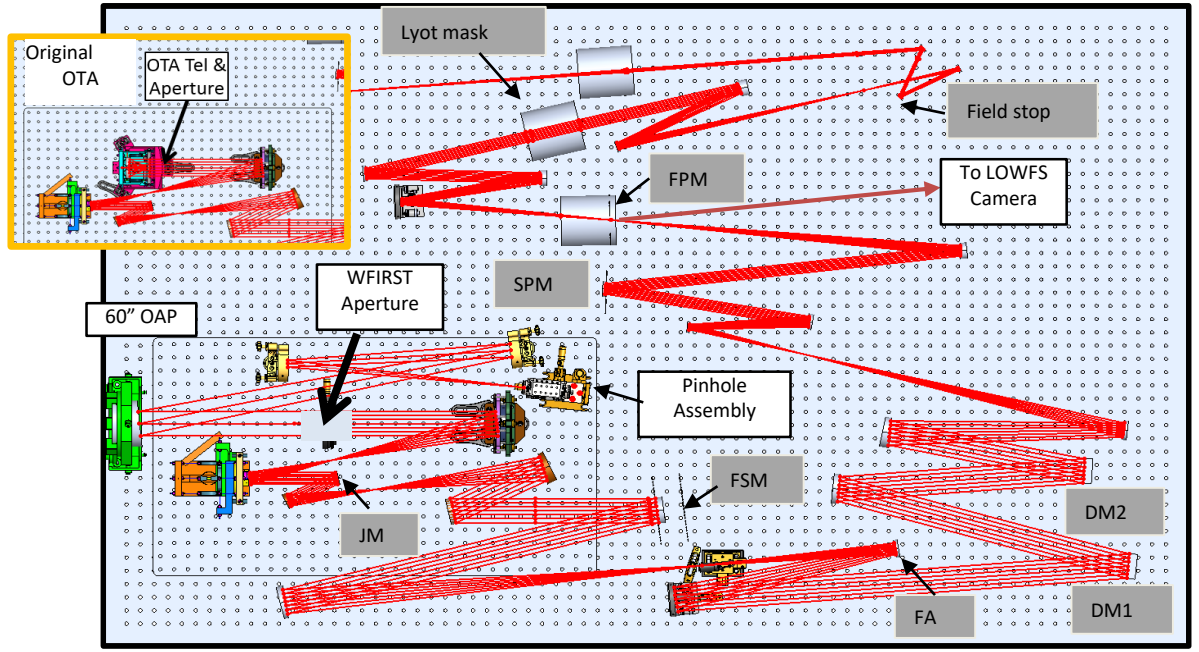
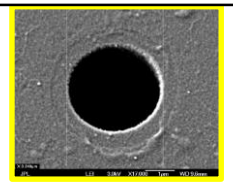


Config.2
3um MDL Pinhole



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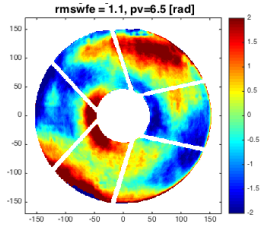
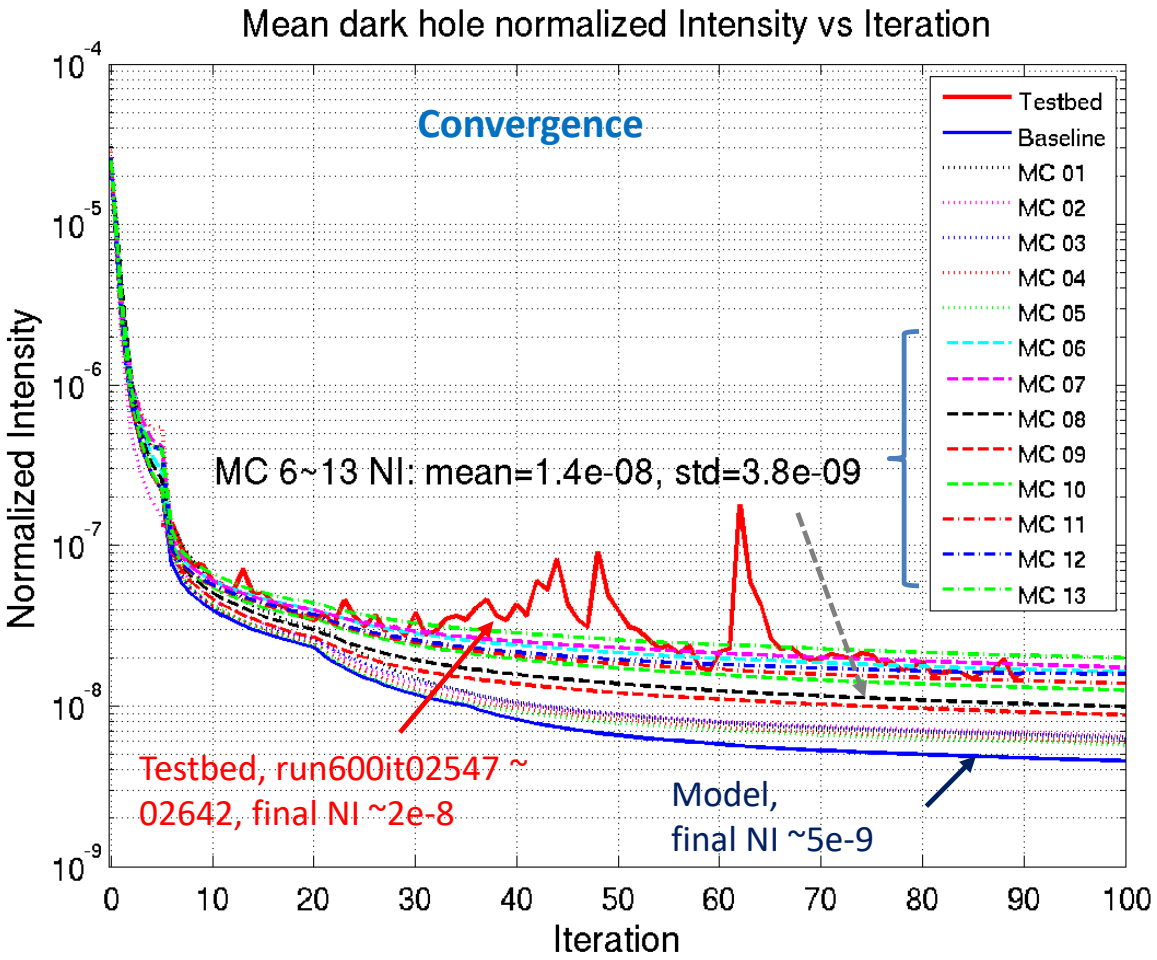
OTA WFE



WFSC Performance: Raw Contrast – *Config.1*

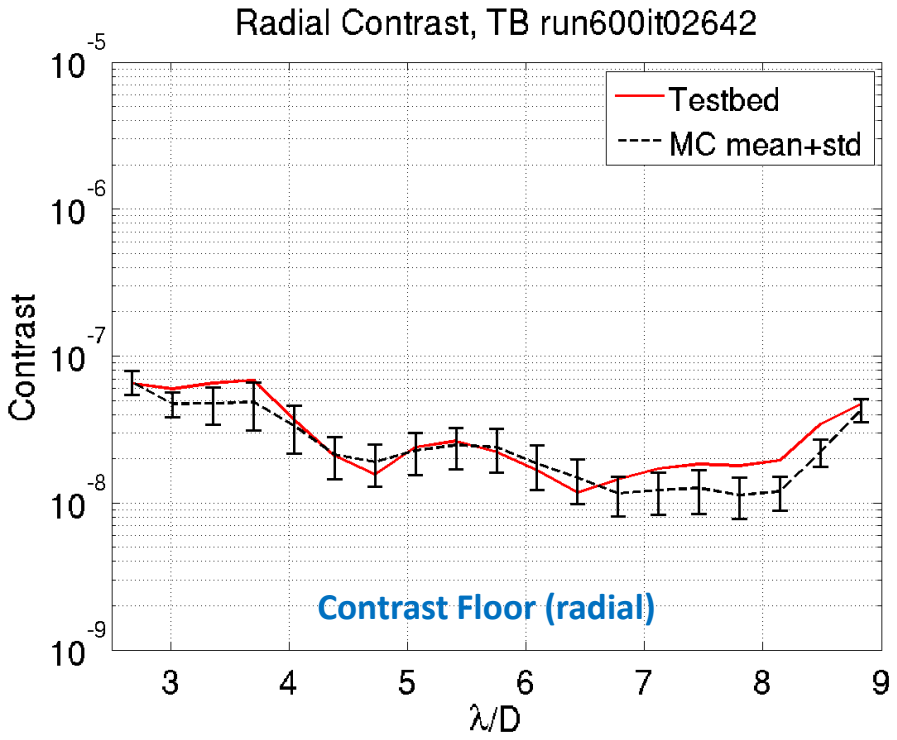
- Good agreement in mean contrast floor w/ MC prediction
- Comparable contrast convergence rate (e.g., MC #12)
  - From ~2e-7 where testbed nulling started
  - Testbed switched from 5λ to 3λ nulling mid course, hence some spikes

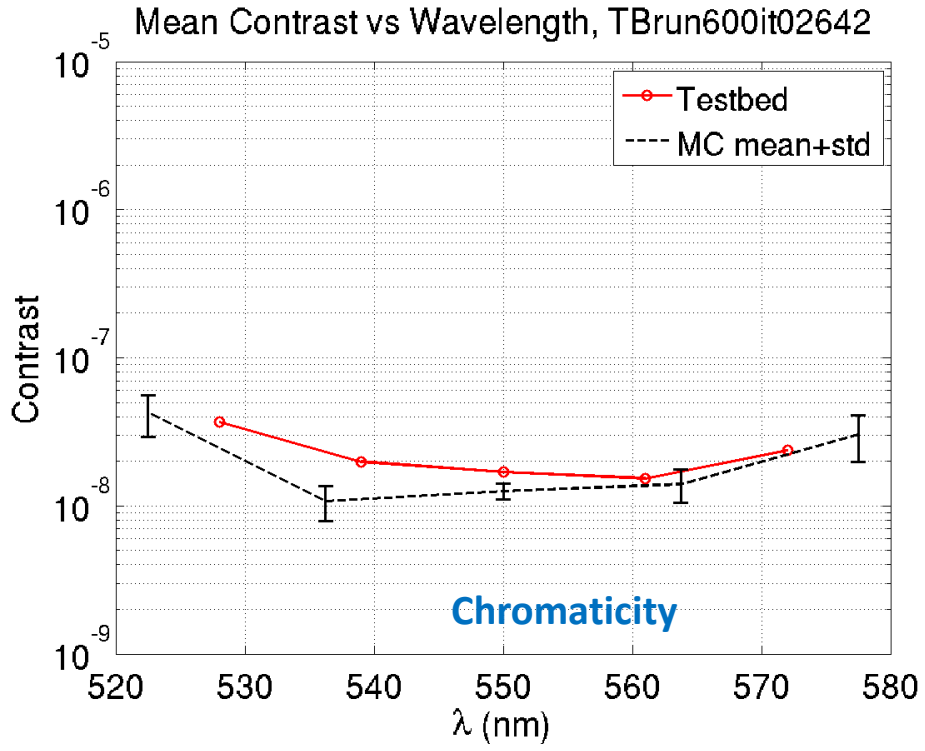


- Large impact of missing knowledge on initial model predictions (dashed lines)
  - Chromatic pupil WFE as result of imperfect hardware used for *simulating star* ➔ not flight relevant specifically
- Small impact of collective knowledge errors (dotted lines)
  - Calibration itself reasonably adequate (if carried out)

WFSC Performance: Radial Contrast & Chromaticity – *Config.1*

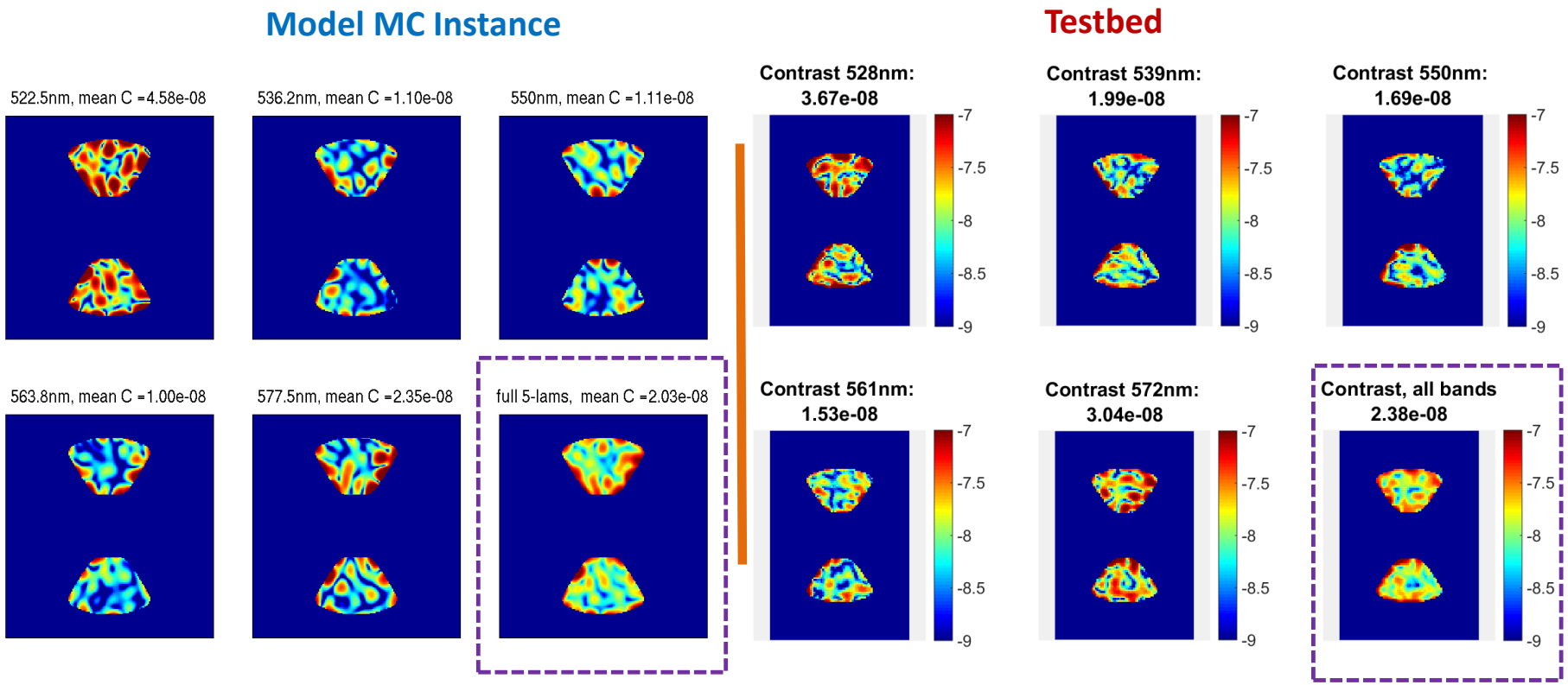
- Good agreement in mean contrast floor & chromaticity w/ MC prediction





WFSC Performance: Contrast Morphology – *Config 1*

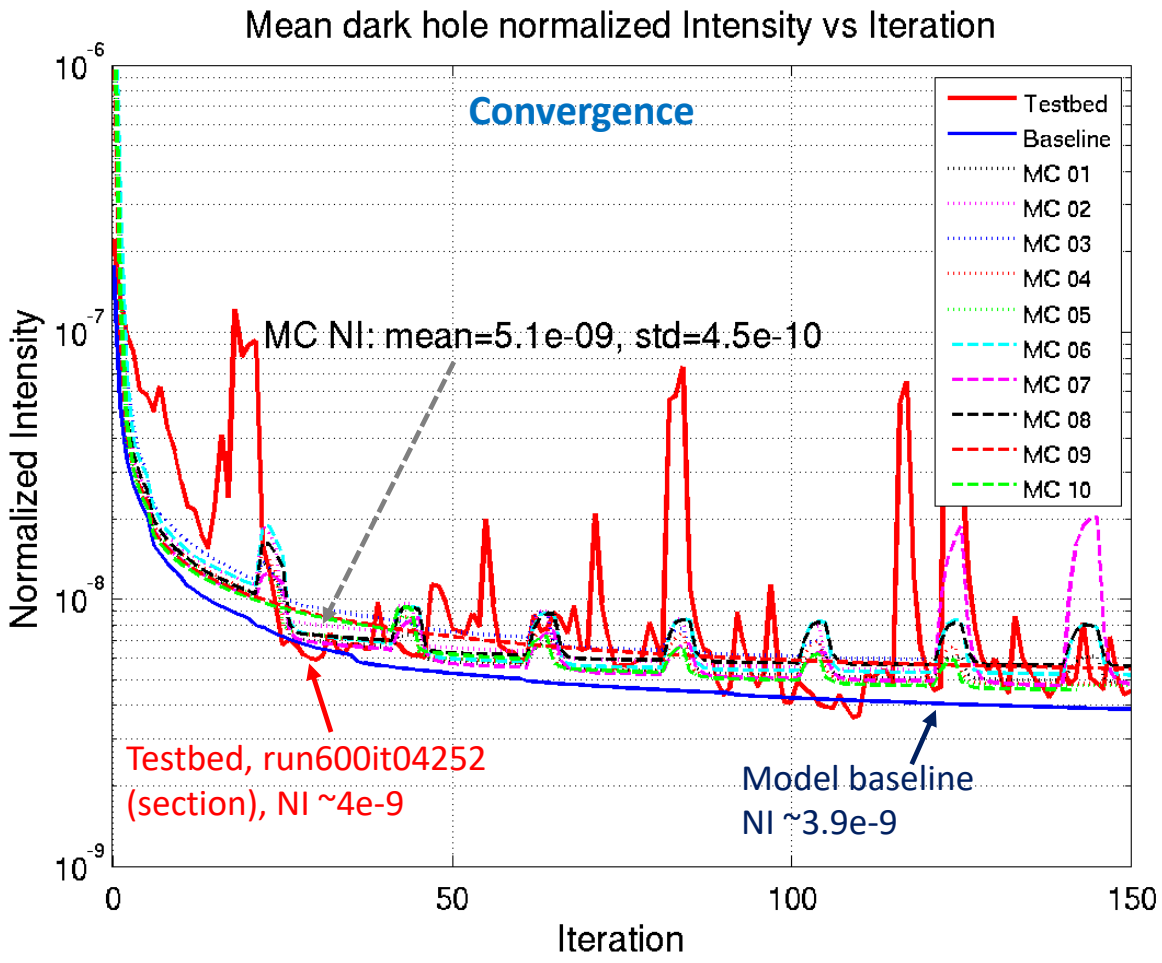
- Good agreement in speckle pattern statistics



(Testbed uses center wavelength of 2% bandwidth; model evaluates contrast using 5 monochromatic wavelengths uniformly spaced over 10% bandwidth)
DH region is 2.5 ~9 λ/D

WFSC Performance: Raw Contrast – *Config 2*

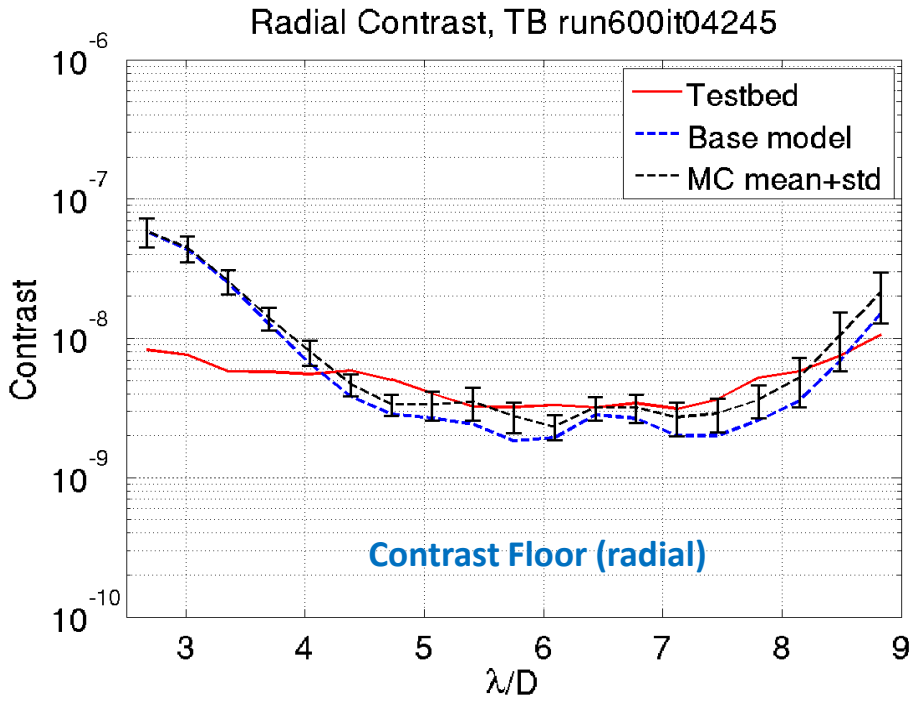
- Good agreement in mean contrast floor w/ base pred.
- Comparable (envelope of) contrast convergence rate
  - From ~2e-7 onward; (most) spikes in iter curves are when using aggressive regularizations

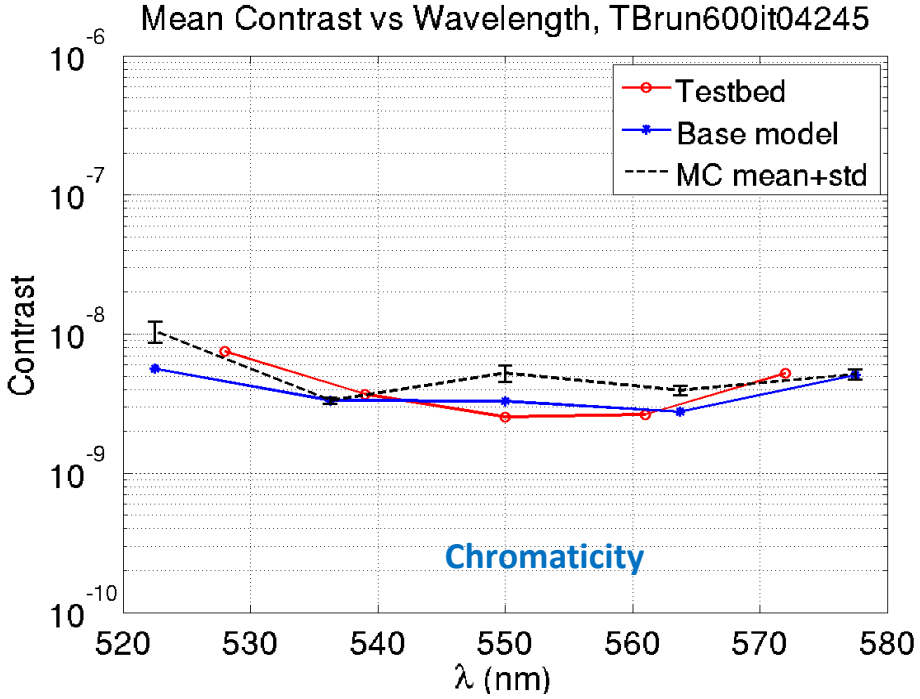


- Testbed result tightly bounded btwn base model and MC predictions
  - Both calibration & calibration errors are adequately captured

WFSC Performance: Radial Contrast & Chromaticity – *Config 2*

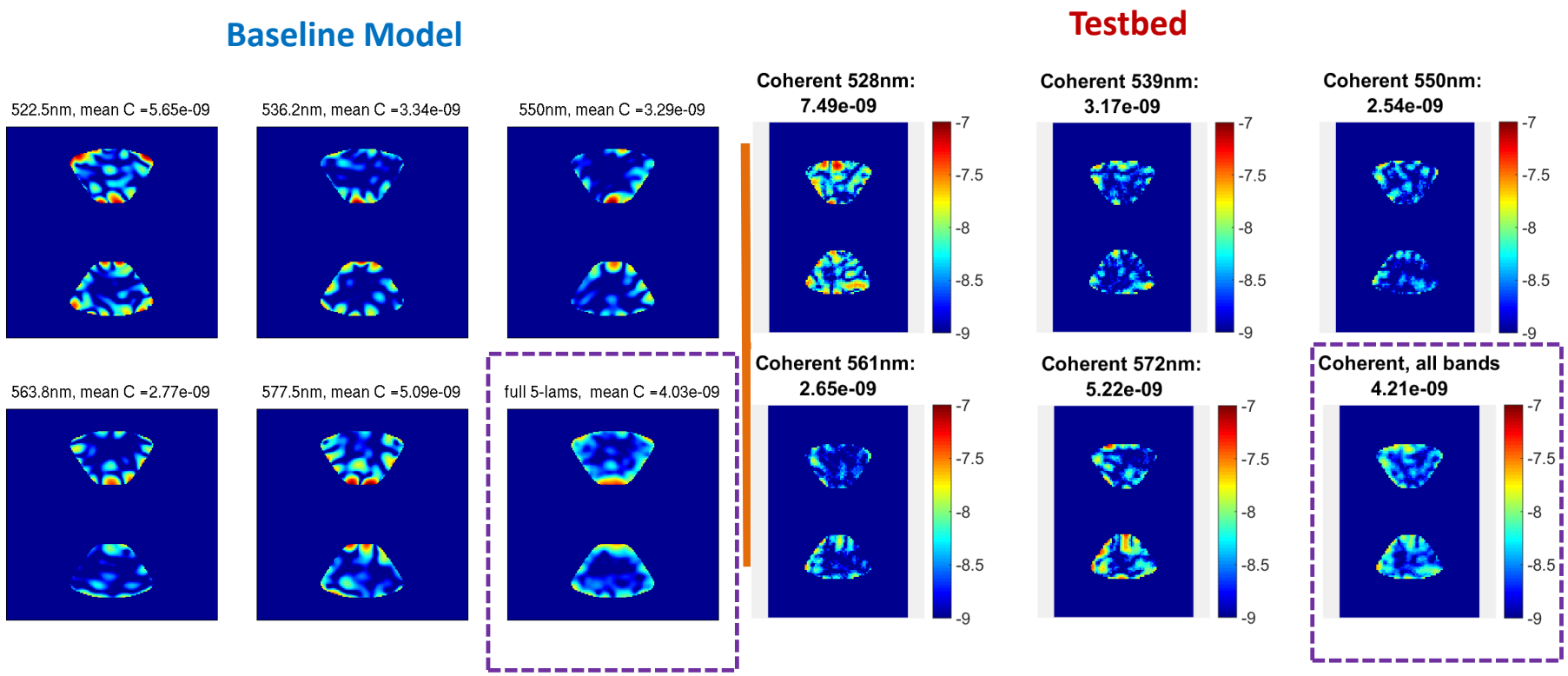
- Good agreement w/ base prediction except < 4Lam/D IWA





WFSC Performance: Contrast Morphology – *Config 2*

- Good agreement in speckle pattern statistics



(Testbed uses center wavelength of 2% bandwidth; model evaluates contrast using 5 monochromatic wavelengths uniformly spaced over 10% bandwidth)

Contrast Sensitivity Comparison - Method

Top stability concerns:

Telescope thermal instability, telescope pointing and jitter, coronagraph mask deployment, etc.

Testbed Zernike injection methods:

1. Apply fitted DM voltages (to Zernike terms) converted from DM gain map on top of its post-nulling dark hole DM setting); scan through +/-2nm rms WFE in 0.2nm step - *main method*
2. *Tip/tilt only*: through controlled injection at jitter mirror
3. *Tip/tilt only*: through image plane occulter mask lateral offset
   conversion scale = 1nm rms /0.13um occulter offset
4. *Focus only*: through source axial (Z) motion
   conversion scale = 1 nm rms/32um linear motion

- alternative methods

Model prediction methods:

1. Apply Zernike directly as *pupil phase* as thermal perturbation would have caused
2. Apply Zernike as fitted *DM voltage* through DM gain map conversion, same as testbed implemented

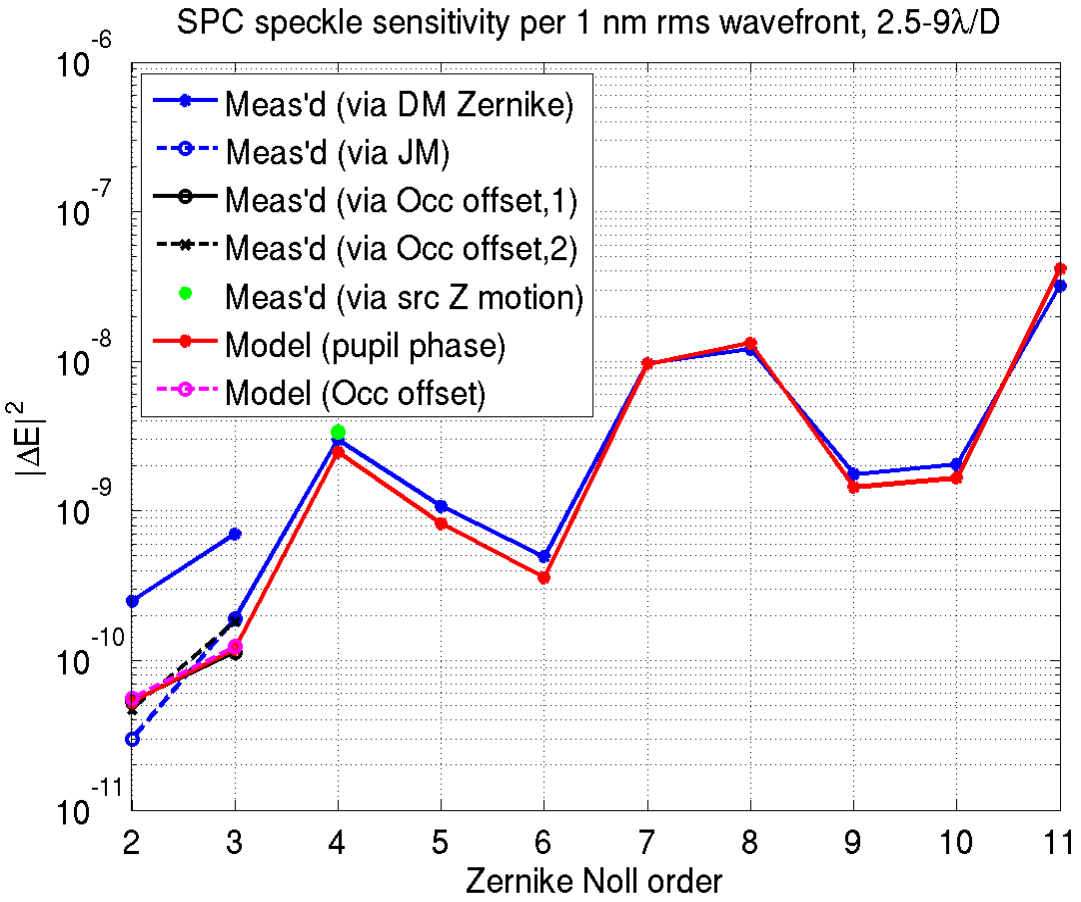
Testbed collected intensity images while metric of interest would prefer speckle field sensitivity:

- Fit the testbed delta intensity image series pixel by pixel to a 2nd order polynomial
- Average of quadratic coef of the fit over dark hole region pixels➔ field sensitivity to Zernike perturbation

All sensitivities are evaluated with *Config.2* model post EFC

Contrast Sensitivity: Zernike LOWFE -1

- Measured: average of pixel fitted ΔNI ➔ field sensitivity to WFE



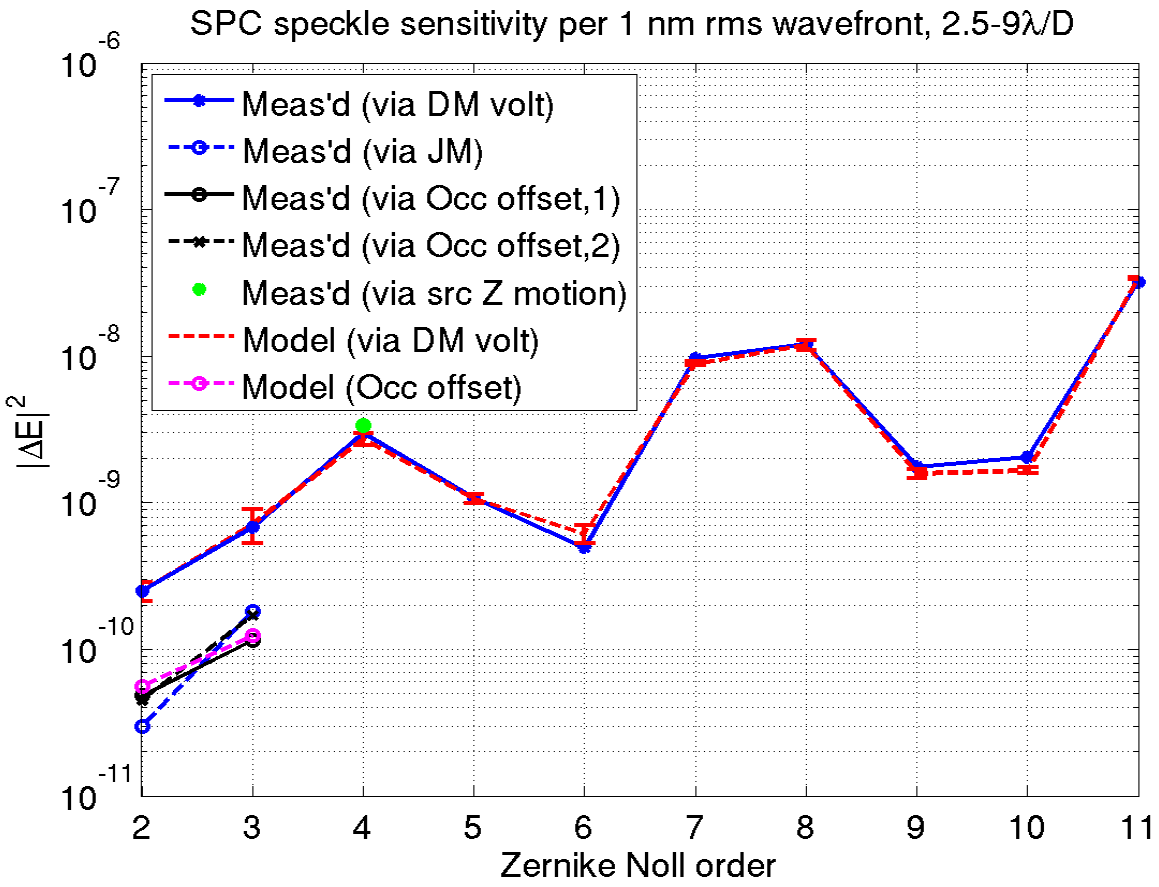
Model: pupil phase

- Z4~11 (via DM or source Z motion):
  - Good match
- Z2Z3 (via DM, JM, & occulter offset):
  - Good match except via DM voltage application

  ➔DM gain error ?

Contrast Sensitivity: Zernike LOWFE – 2

- Measured: average of pixel fitted ΔNI ➔ field sensitivity to WFE



Model: DM2 volt + gain error

- DM gain error responsible for DM Z2Z3 mismatch in pupil phase model prediction
  - Best fit gain error ~6% rms; in line w/ "typical" DM gain error estimate
- Fractional error < 25%
  - Mean ~9%

Zernike	Fractional err (%)
Z2	0
Z3	5
Z4	-11
Z5	-1
Z6	19
Z7	-9
Z8	-2
Z9	-11
Z10	-23
Z11	6

Consistent sensitivity predictions by multiple methods (on testbed and in model)

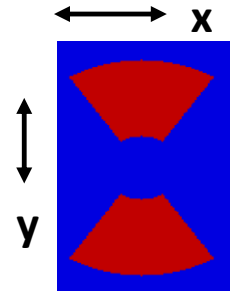
Contrast Sensitivity: Occulter Mask Shear

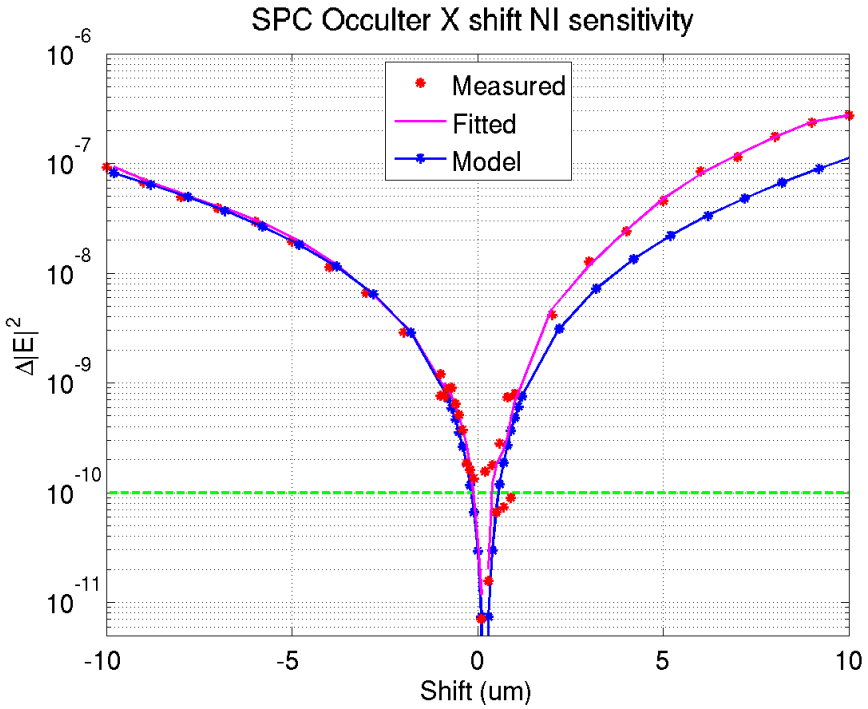
(& Filter Wheel Mechanism Error Budget Verification)

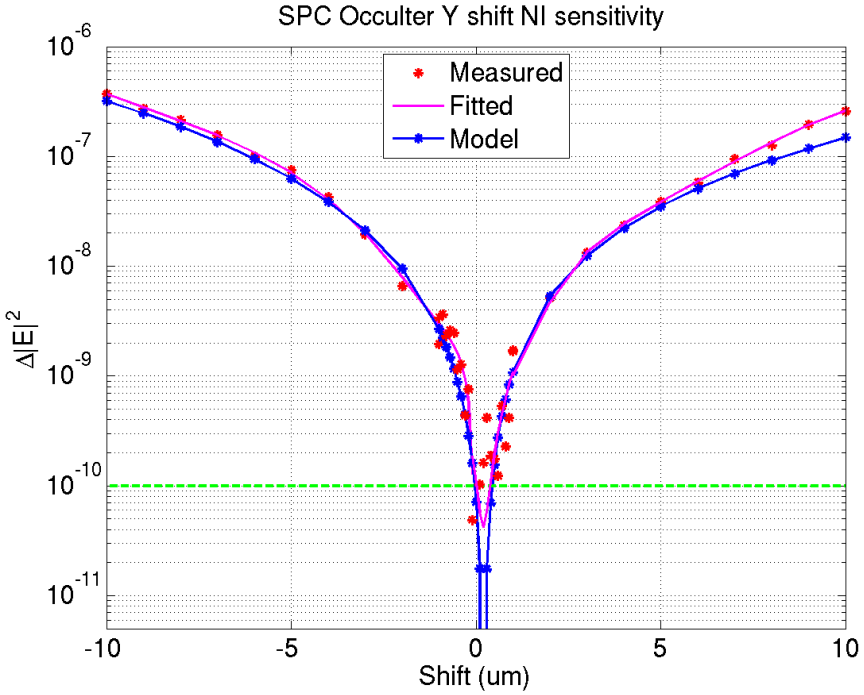
- **Testbed :** scan occulter in x & y directions in coarse steps of 1um & fine steps of 0.1 um

❖ Good agreement btwn model prediction & testbed data out to the limits of the relevant error budge range

	X , Y for ΔC =1e-10		Tip/tilt sensitivity (Extrapolated)	
Measurement, fitted	~0.35um	~0.20um	1.4e-11	4.2e-11
Model, *Config.2*	~0.38um	~0.24um	1.4e-11	2.9e-11
Fractional Error: | T – M | / T	9%	20%		





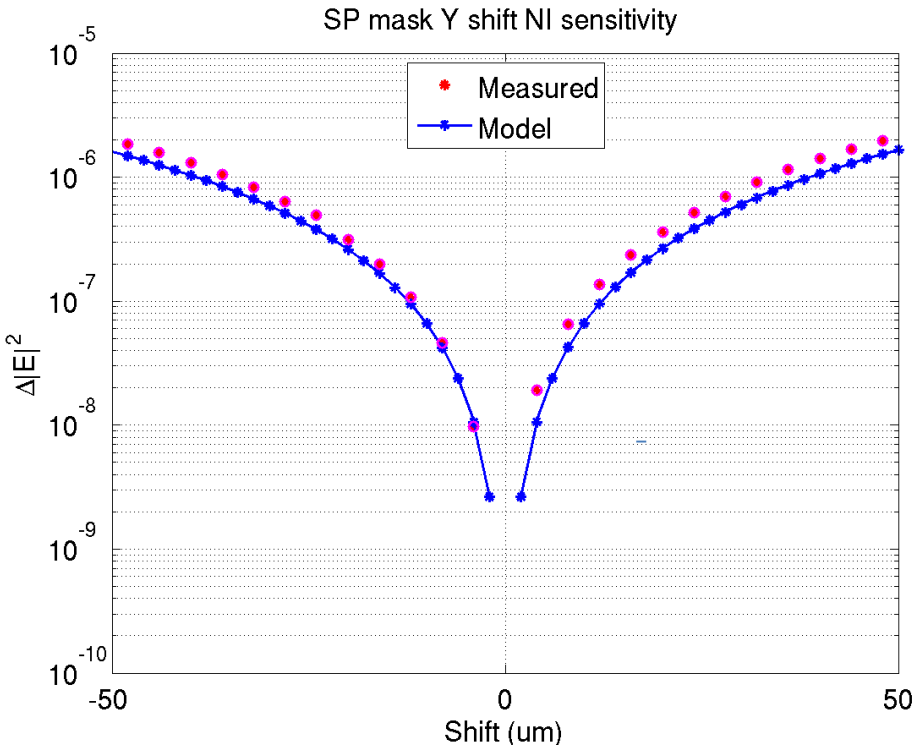


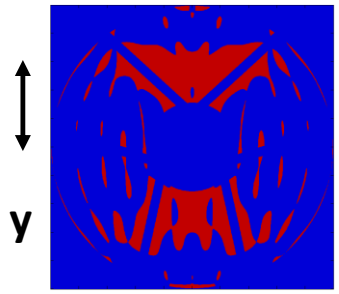
Contrast Sensitivity: Shaped Pupil Mask Shear

Testbed: Move shaped pupil mask y-axis in coarse steps of 4um (limited by testbed hardware motion)

- Good agreement between testbed measured and model prediction

Y shifts	for ΔC =1e-8
Measured	~3um
Model, *Config.2*	~4um
Fractional Error	~33%





OMC Testbed SPC Modeling - Summary

- Tested SPC model fidelity under different testbed HW/SW configurations & in a number of metrics
- Achieved good or excellent agreement between model predictions and testbed results:
  - Contrast floor: mean <30%; chromaticity ~34% avg
  - Contrast convergence rate: comparable
  - Contrast sensitivity:
    - Low order Zernike Z2~11 WFE: all < 25%; avg ~ 9%, at 1nm rms
    - Occulter mask lateral shear: <20%, at 1e-10 ΔC
    - Shaped pupil mask lateral shear: ~33%, at 1e-8 ΔC

- Lesson learned:
  - Incomplete model has large impact on WFSC performance prediction
    - Chromatic pupil aberration on testbed (*not flight relevant!*) was the cause in early contrast gap; Improved contrast agreement in later model (and contrast on testbed as well) after inclusion
  - Importance of incorporating key WFSC features as in use
    - e.g., probing and control strategies (EFC regularization, Jacobian updates), voltage constraints

- Room to further improve model fidelity:
  - Radial contrast in *Config*.2 prediction near IWA

APPENDIX

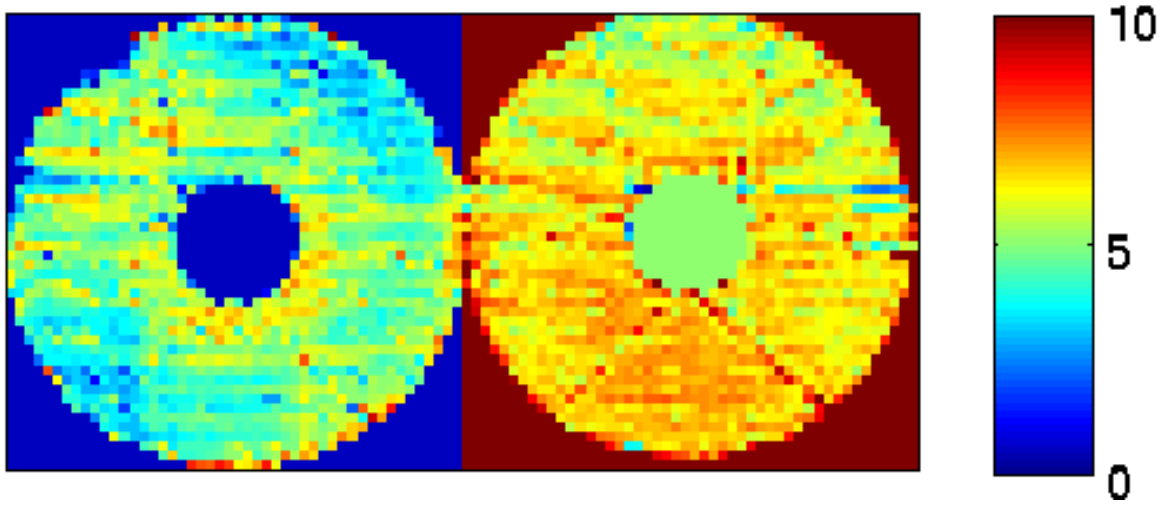
Backup slides

Known TB Imperfection – DMs Offsets & Gains

- DM registration offset (from E. Cady, 8/16/2016, for Config.1; minor adjustment for config.2):

	DM1	DM2	DM1/DM2 relative	
Scale x (pixpermmx)	6.6161 pixel/mm	6.5882 pixel/mm		
Scale y (pixpermmy)	6.5382 pixel/mm	6.6075 pixel/mm		
Decenter x (dx)	-1.304 pixel	0.2173 pixel	1.52 pixel	230.5 um
Decenter y (dy)	-0.7704 pixel	5.8912 pixel	6.66 pixel	**1009.4um**
Clocking (thact, clockwise)	-90.88 deg	-89.60 deg		**1.28 deg**

- DM gain maps



- Additionally, DMs also follow constraints:
  - 1) Stroke range [0 ~100] V, with bias at 50V for DM1, 30V for DM2
  - 2) Difference in neighboring acts voltage < 30 V

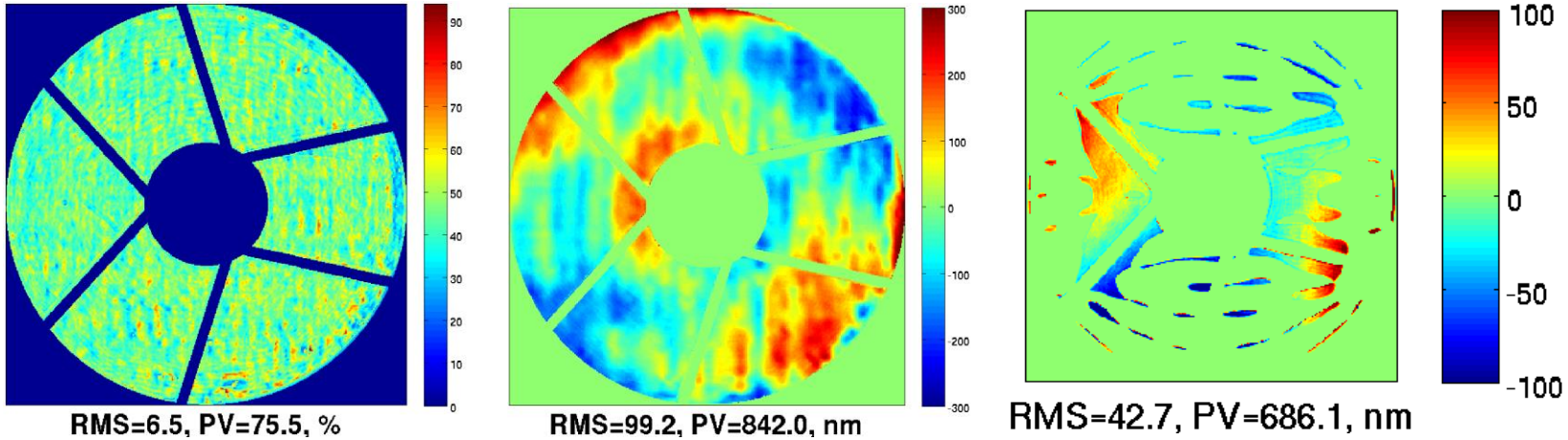
Known TB Imperfection - Pupil Aber @ 550nm

- Measured pupil phase and amp BEFORE flattening are used as input to model

Pupil Amp | **Pupil Phase** | **SP mask WFE**

Config 1

OTA, w/ COTS 1um pinhole



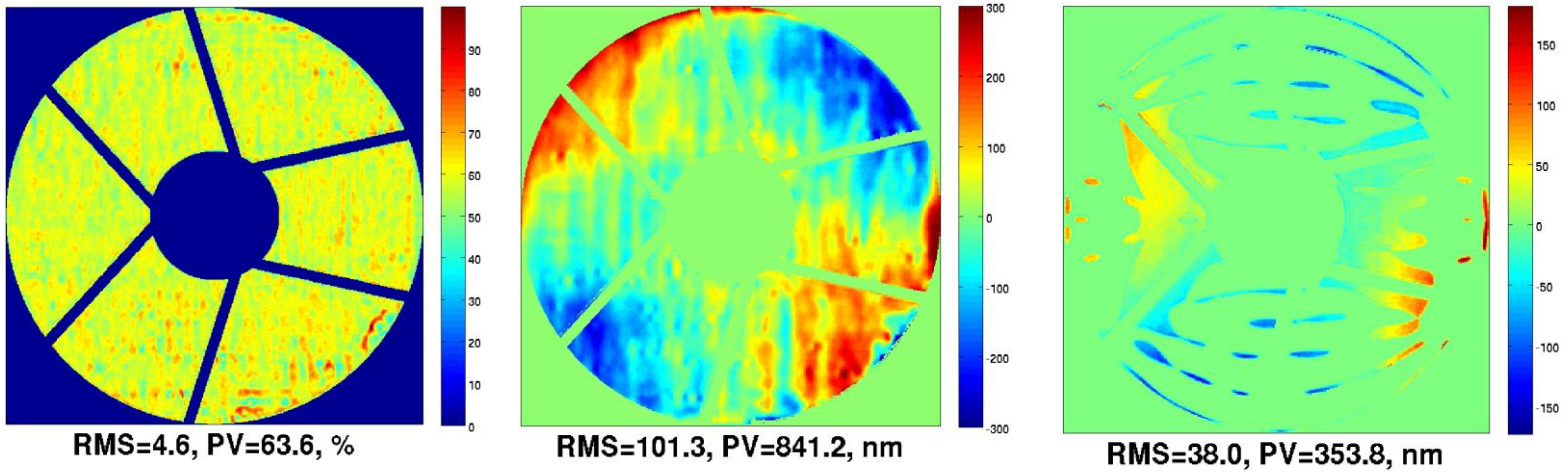
RMS=6.5, PV=75.5, %

RMS=99.2, PV=842.0, nm

RMS=42.7, PV=686.1, nm

Config 2

No OTA, w/ MDL 3um pinhole



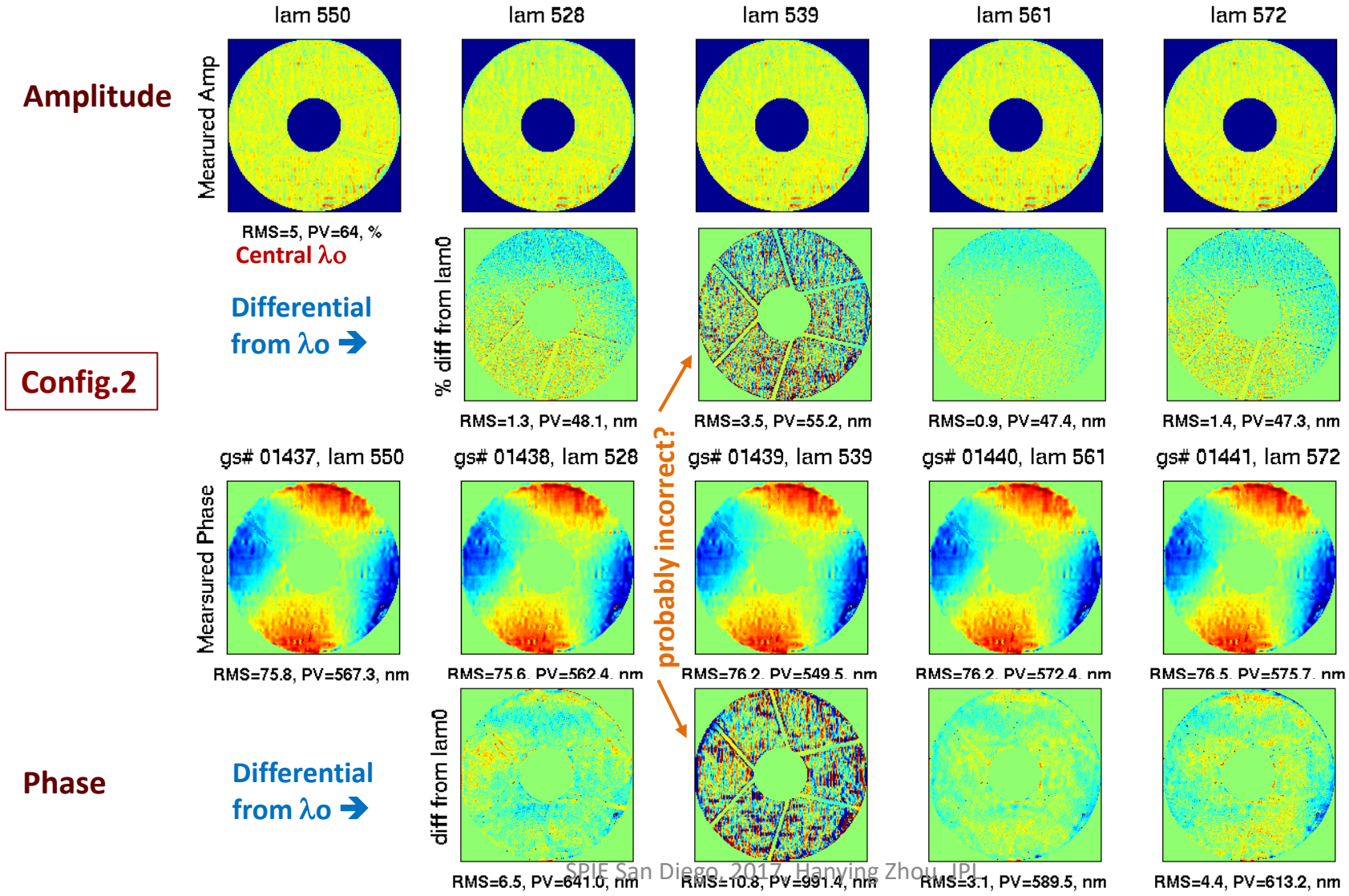
RMS=4.6, PV=63.6, %

RMS=101.3, PV=841.2, nm

RMS=38.0, PV=353.8, nm

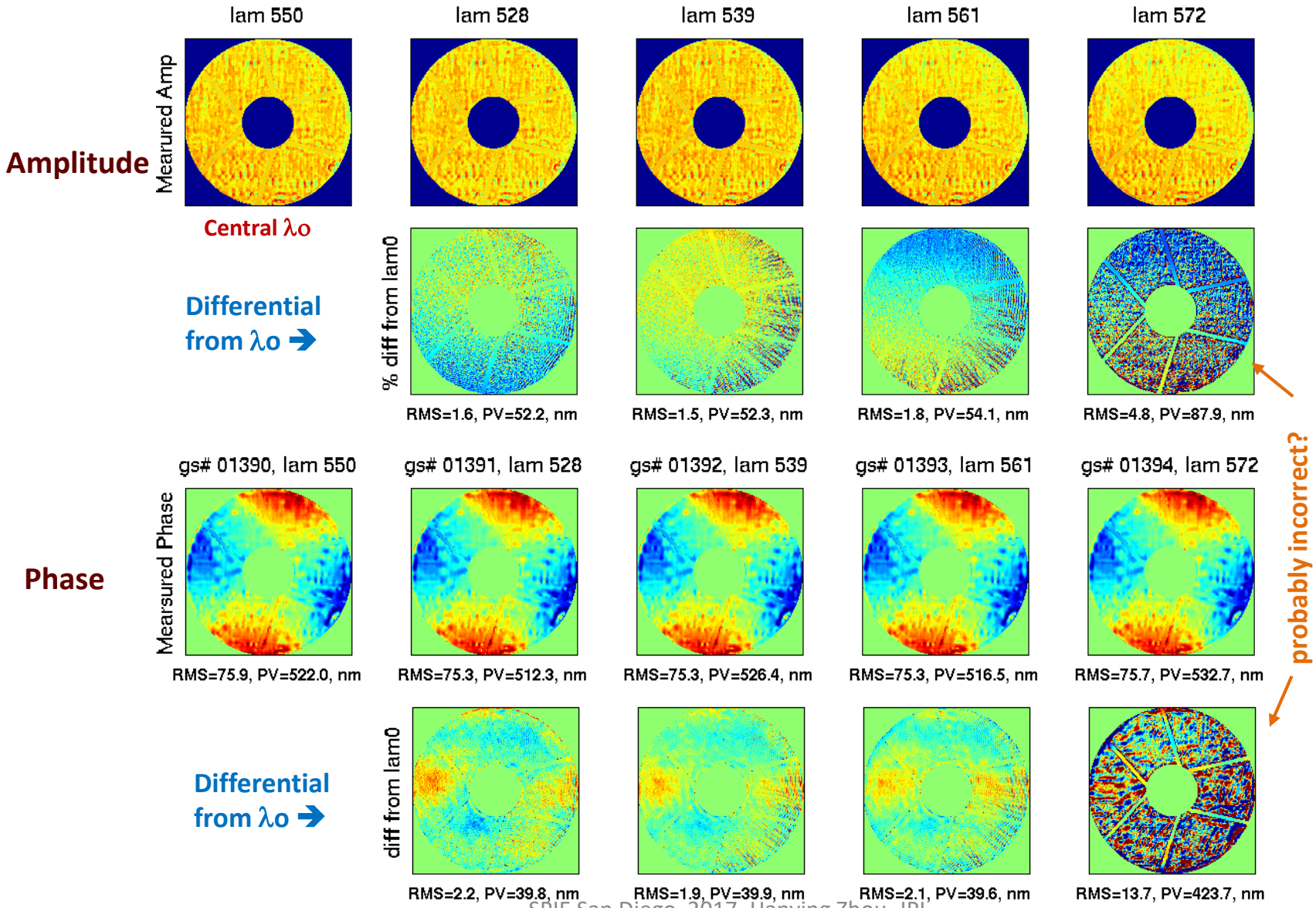
Known Imperfection – Chromatic Pupil Aber

- *Only low order components of the differences used in model for chromatic aberration*
  - Current pupil PR measurement *does not* remove *potential corruption from down stream optics*
  - PR measurement/process itself is also imperfect (e.g., @ 539nm lam below)



Imperfect PR Meas. – Chromatic Pupil Amp

- NO OTA, COTS 3um pinhole - notable wavelength dependent pupil amp



List of Estimated Error Uncertainty Bounds for SPC

	Parameter Name	Estimated Error Upper Limit	Note
DM gain & alignment	DM (lateral) decenter	75 um	
	DM rotation	[0 0 0.3] deg	[tip tilt clocking]
	DM gain	10 pct	
SPM alignment & manufacture error	SPM (lateral) decenter	32 um	
	SPM rotation	[0 0 0.25] deg	[tip tilt clocking]
	SPM undercut	1 um, all sides	Fixed in all MC instances
Occulter alignment	Occulter (lateral) decenter	1 um	
	Occulter defocus	100 um	
	Occulter rotation	[0 0 0.5] deg	[tip tilt clocking]
Lyot Stop alignment	Lyot stop lateral decenter		
	Lyot stop rotation	[0 0 0.5] deg	[tip tilt clocking]
Source alignment	Source lateral shift	0.125 λ/D	
Pupil amp error (Achromatic)	pupil amp zernike term	2:3	slope-like amplitude droop
	Pupil amp zernike rms	2 pct	
	Pupil amp high order		From difference of repeat flat DM pairs mears
	Pupil amp PSD rms	2 pct	
Pupil WFE (Achromatic)	Pupil WFE Zernike term	5:15	
	Pupil WFE Zernike rms	0.05rad @550nm	drift/change since last measured
	Pupil WFE PSD		From difference of repeat flat DM pairs mears
	Pupil WFE PSD rms	1.5 nm	
SPM WFE	SPM zernike term	15	
	SPM zernike rms	0.05rad @550nm	less accurate PR due to thin edges of mask
	SPM PSD params		= [SPdiam/pupil_diam spm_psd_rms 4 3]
	SPM PSD rms	1.5 nm	
Chromatic pupil WFE & amp	Pol amp	2 pct, 1 pct	+/- slope-like Z2Z3 at end bands, λ dependent
	Pol WFE	7 nm, 0.07 nm	+/- Ast (Z5Z6) at end bands, λ dependent

- Calibration errors are assumed of simple Gaussian distribution
- Most error bounds were estimated / suggested by testbed team
- Chromatic errors for *config.1* are based on pinhole and MCB polarization modeling, as well as measured pupil amp profiles; reduced for *config.2* as OTA removed & pinhole replaced
- Each error instances are generated as:

$$e_i^j = range_i * trunc\_randn(j)/trunc\_\sigma$$

w/ truncation done at +/-2 σ

circled are additions or major change in config.2

Coronagraph

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