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Closing the Contrast Gap Between Testbed and Model Prediction with WFIRST-CGI Shaped Pupil Coronagraph

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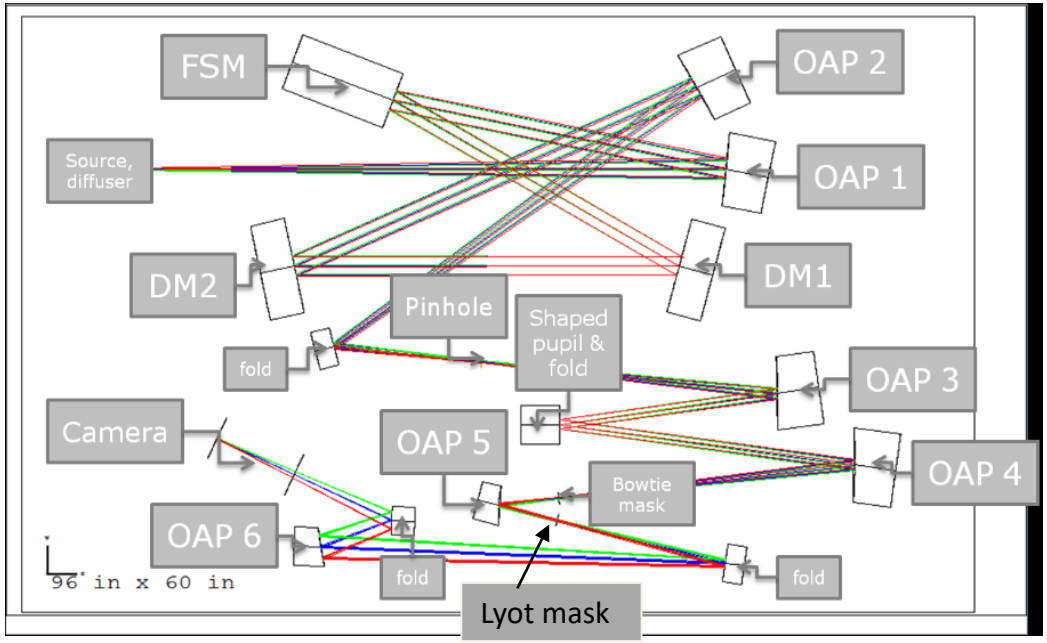
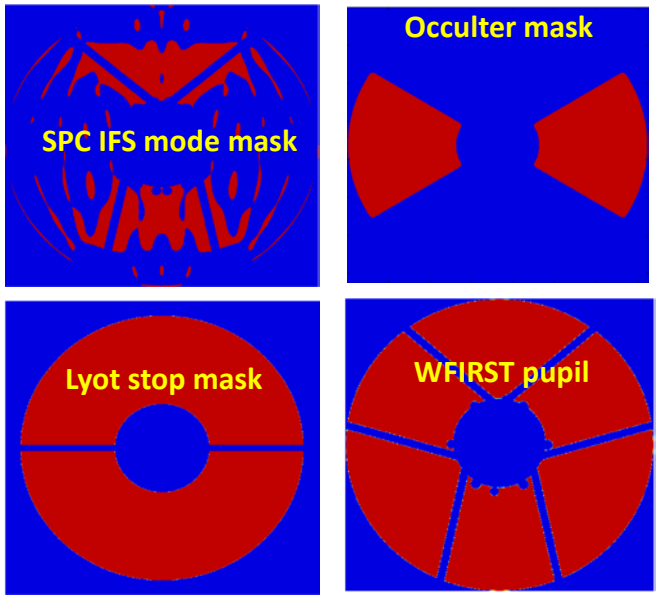
WFIRST CGI and Shaped Pupil Coronagraph (SPC) Testbed

- SPC: One of the baseline architectures of coronagraph instrument (CGI) design in proposed NASA WFIRST (Wide-Field InfraRed Survey Telescope) mission
- It uses binary masks to reshape telescope pupil diffraction into a high contrast dark hole region at image plane
  - Current design (by Princeton U.) uses a set of three masks (IFS mode shown below right), for WFRIST obscured pupil
- SPC testbed (one of two HCITs at JPL) layout schematic below left

WFIRST CGI:
Direct Planet Imaging
Spectral Characterization
Dust debris characterization



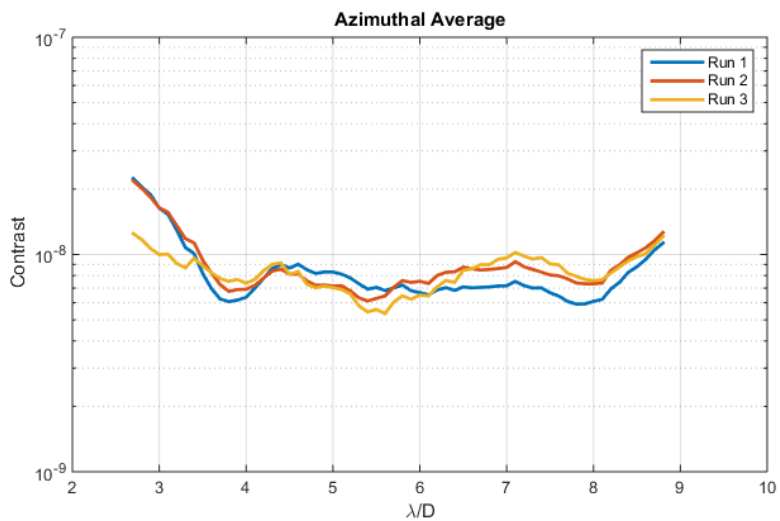


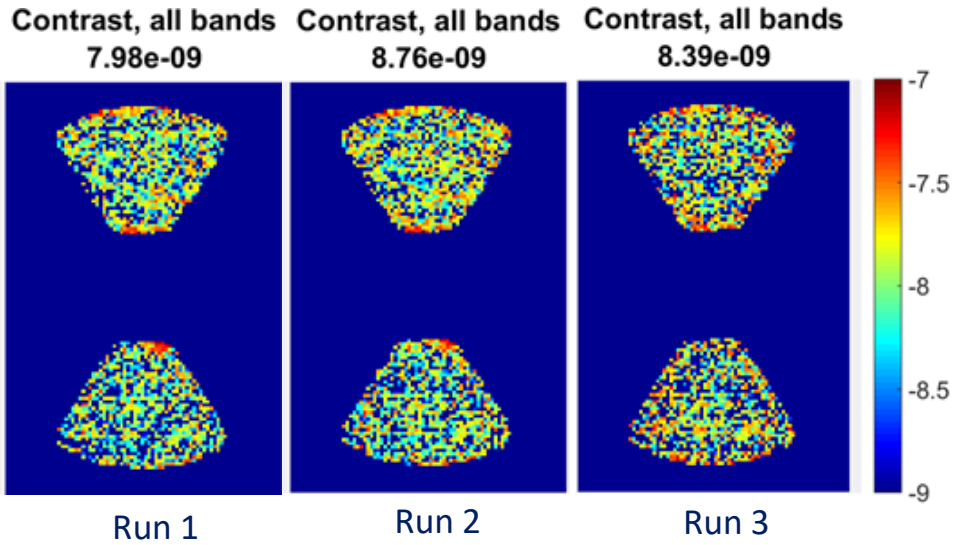
Milestone 5 SPC Testbed Results Summary*

Sequence of technology development milestones, SPC related:

- MS1: Mask fabrication & characterization
- MS2: Narrowband (2%) contrast 1e-8 demonstration with obscuration pupil
- MS5: Broadband (10%) contrast 1e-8 demonstration with obscuration pupil

- Three runs on three days, simultaneously controlling over five 2% bands spanning 522.5-577.5nm (10% around 550nm)
- 2-sided dark hole over 65° wedge, 2 DMs, ~2.8-8.8 λ/D WA
- Corrected for off-axis coronagraph throughput ("contrast" rather than "normalized intensity")
- All three runs <8.8x10^{-9} over 10% band



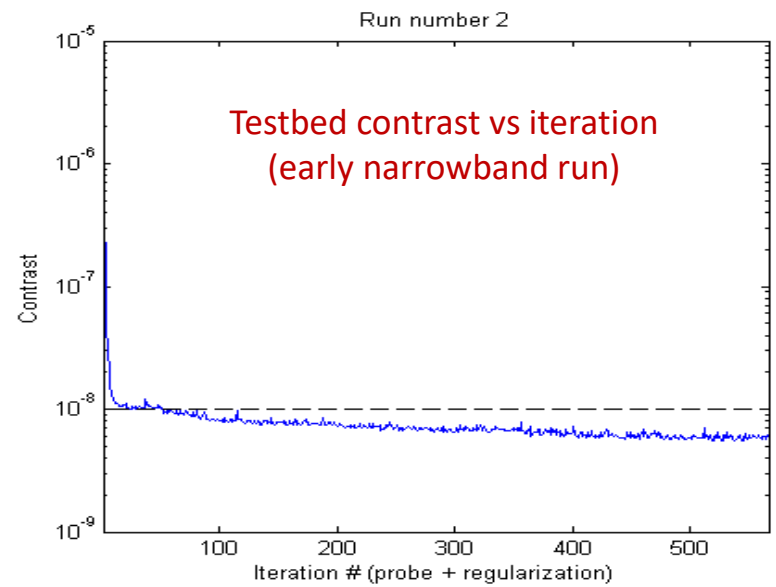


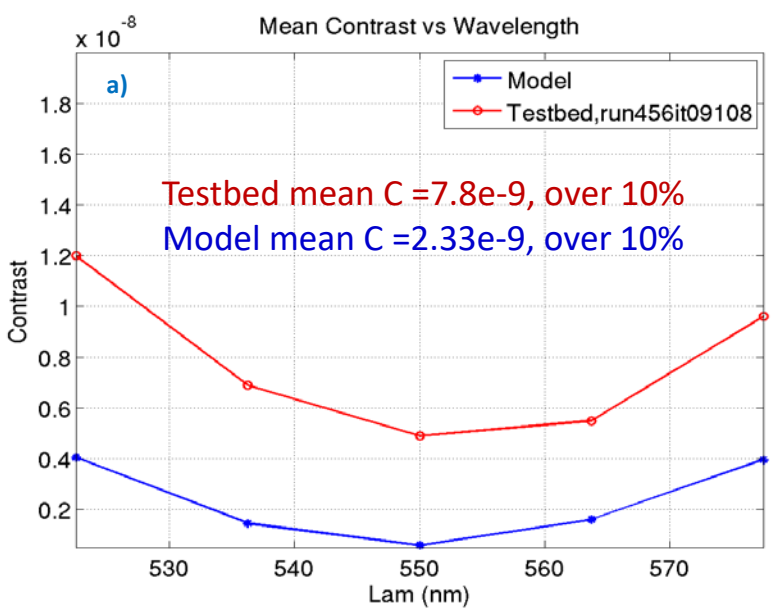
** Cady E., et al, Proc. SPIE. 9904, (this conference), (2016)*

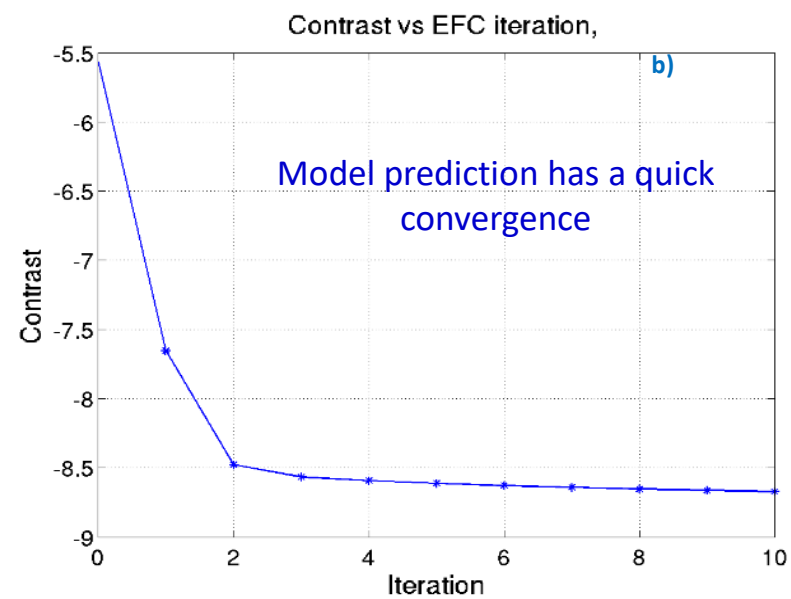
Performance Discrepancy at the Time of MS5: SPC Testbed vs Model Predication

Compared w/ model prediction:

- Testbed mean contrast floor was about ~3.5x worse
- Contrast convergence was at least an order of magnitude slower; typically a few hundred iterations to achieve convergence (starting from flat DM)







Move Forward for Milestone 9: Close the Contrast Gap

- For MS9, need to close the contrast performance gap:
  MS9: Broadband (10%) contrast 1e-8 demonstration with dynamic WFE input, model validation

- **Areas that are potentially sensitive/critical in reaching designed contrast**:
  1. DM actuator poke response, or Jacobian
  2. Changes in testbed optics layout (distance) versus model assumed
  3. System WFEs, particularly the low order WFE of shaped pupil mask
  4. Distortion in shaped pupil mask amplitude
  5. …

- Early findings:
  - DM1 was displaced from the pupil location (by design) along the optical axis by a large amount (~230mm) ➔ insignificant improvement after fixing
  - Difficulty in improving the pupil WFE estimation accuracy due to the large obscuration of the shaped pupil mask; its large dark horizontal area renders estimation of astigmatism difficult.

Focus subsequently centered on checking testbed control Jacobian

- Accurate control Jacobian is key to successful WFSC

Jacobian and Its Testbed Measurement

- Jacobian: collection of individual act's delta poke's image plane (complex) field response per unit poke strength, G_k, in linear approximation:

$$G_k = C\left\{E_{pup}\exp\left(i\phi_{dm,k}\right)\right\} - C\left\{E_{pup}\right\} \approx iC\left\{E_{pup}\phi_{dm,k}\right\} \quad (1)$$

E_{pup}: pupil E field; $\phi_{dm,k}$: kth act poke for Jacobian; C: linear coronagraph operator

- To measure Jacobian, use pair-wise DM probing*

$$I_j^{+/-} = \left|E_G \pm \Delta P_j\right|^2 + I_{inc} = \left|E_G\right|^2 + \left|\Delta P_j\right|^2 \pm 2\,\Re\left\{E_G^*\Delta P_j\right\} + I_{inc} \quad (2)$$

$$\Delta I_j \equiv I_j^+ - I_j^- = 4\Re\left\{E_G\Delta P_j\right\} \quad (3)$$

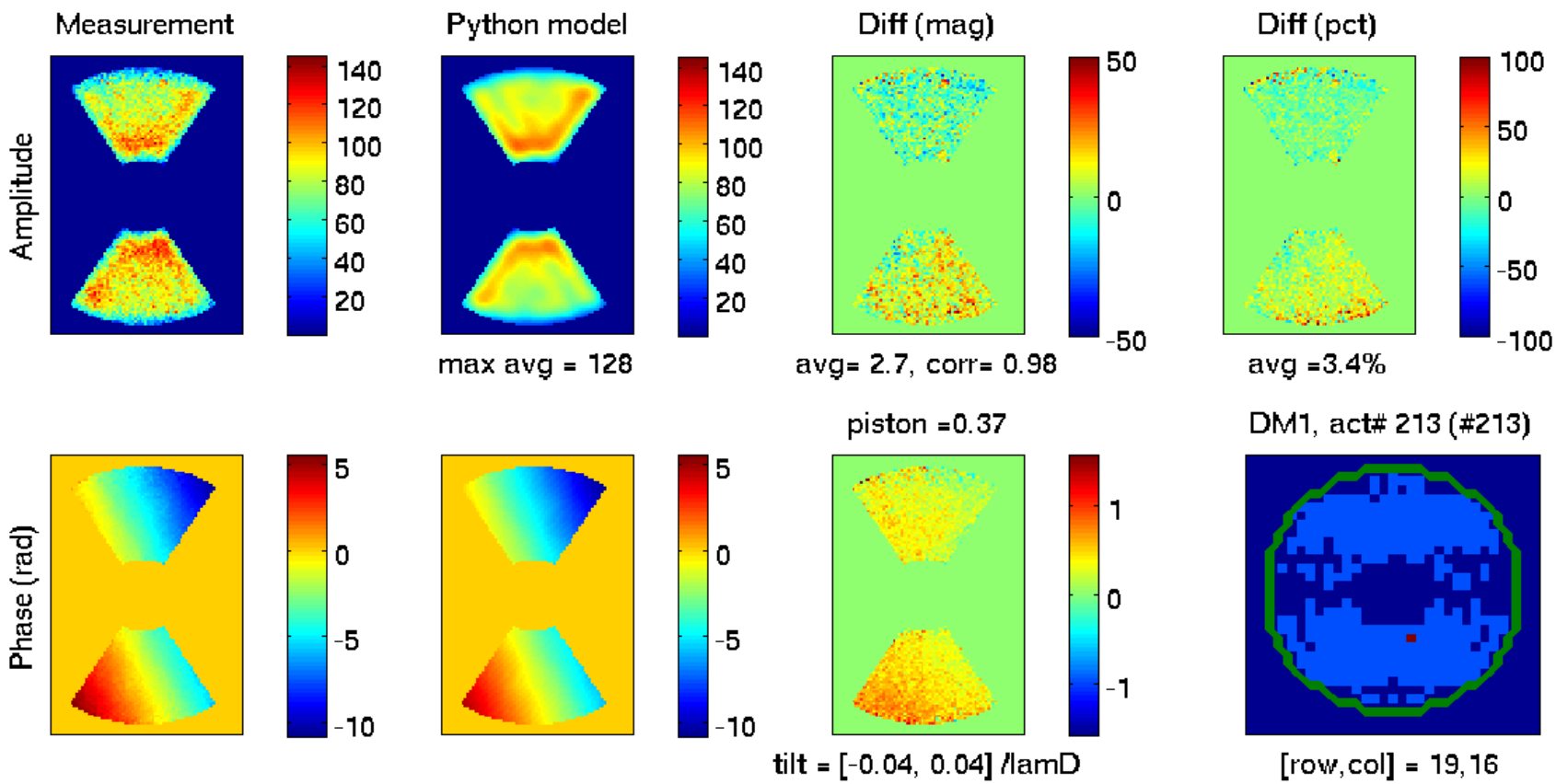
$$\begin{bmatrix}\Delta I_1\\ \vdots \\ \Delta I_N\end{bmatrix} = 2\begin{bmatrix}-\Im\{\Delta P_1\} & \Re\{\Delta P_1\}\\ \vdots & \vdots \\ -\Im\{\Delta P_N\} & \Re\{\Delta P_N\}\end{bmatrix}\begin{bmatrix}\Re\{E_G\}\\ \Im\{E_G\}\end{bmatrix} \quad (4)$$

$E_G = C\{\ \}$: to-be-measured image plane field from DM poke; ΔP_i: probing field, obtained by propagating DM probe patterns through the coronagraph model

- Measured testbed Jacobian:
  - 3 pairs of positive-negative DM probes plus a no-probe images
  - In amplitude (direct measurement, $\sqrt{\left(I_j^+ - I_j^-\right)/2 - I_o}$) and phase (derived, measurement + Eq.4)
- Testbed control Jacobian:
  - Simple forward propagation of the ΔDM poke w/ the coronagraph model and Eq.1

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

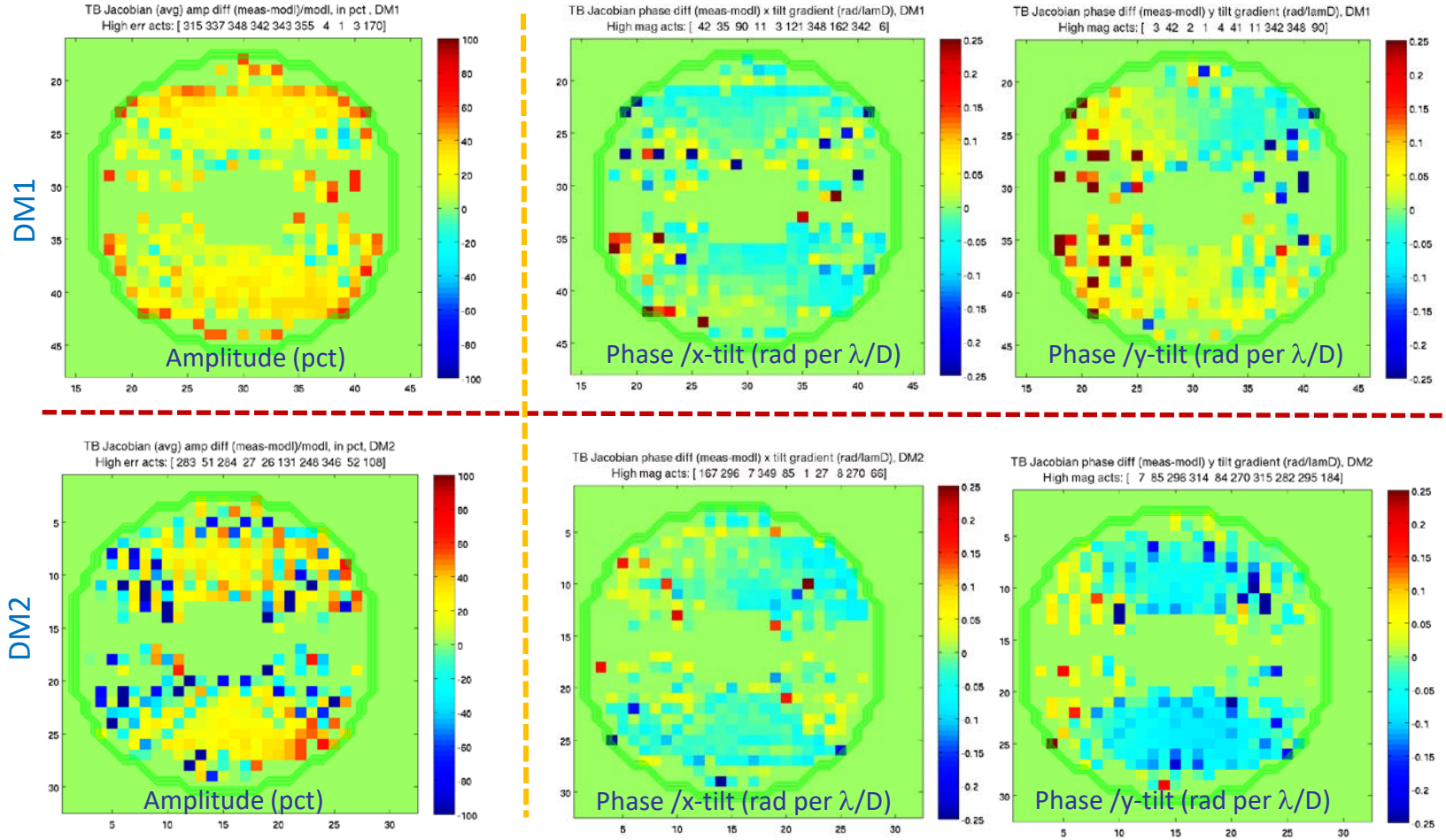
Example of Testbed Jacobian: Measurement vs Model Prediction



- Top right: amplitude error in % of difference: (meas-model)/model
- Bottom 2nd right: phases error (in rad), and its x-, y- tilt gradient (per λ/D)
- Bottom right: the act location being poked (red dot) against all active actuators (light blue)

Note: "measured" phase is derived from model through probing procedure

Testbed Jacobian Error 2D Map: Amplitude and Phase



Amp error (left col)

Phase error (right two cols)

Error metrics:

- **Amp. Error in %:** (meas-model)/model
- **Phase error:** tilt gradient (per λ/D)

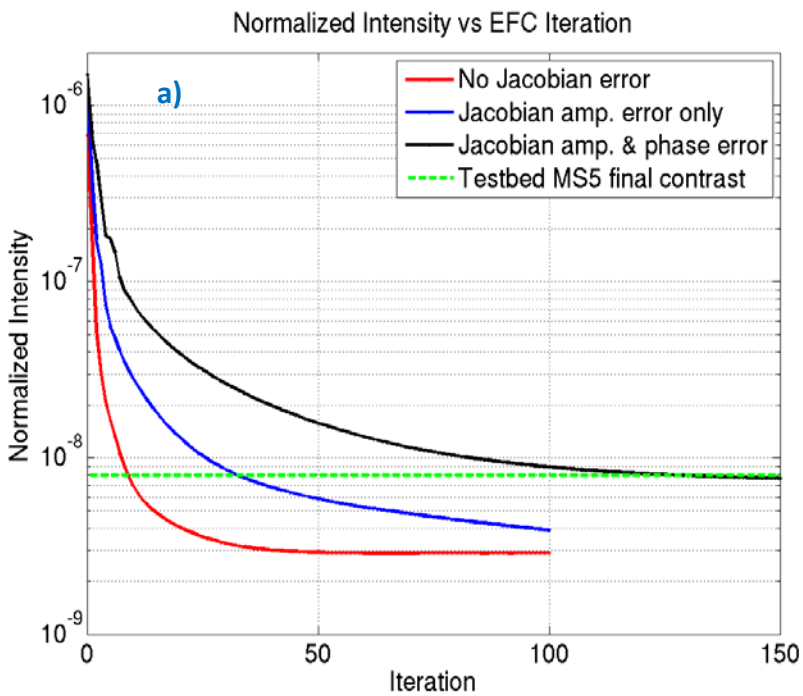
- Both DMs have mean Amp. error ~25%
- Phase error is on the order of 0.05 rad per λ/D
  - Spatially correlated distribution

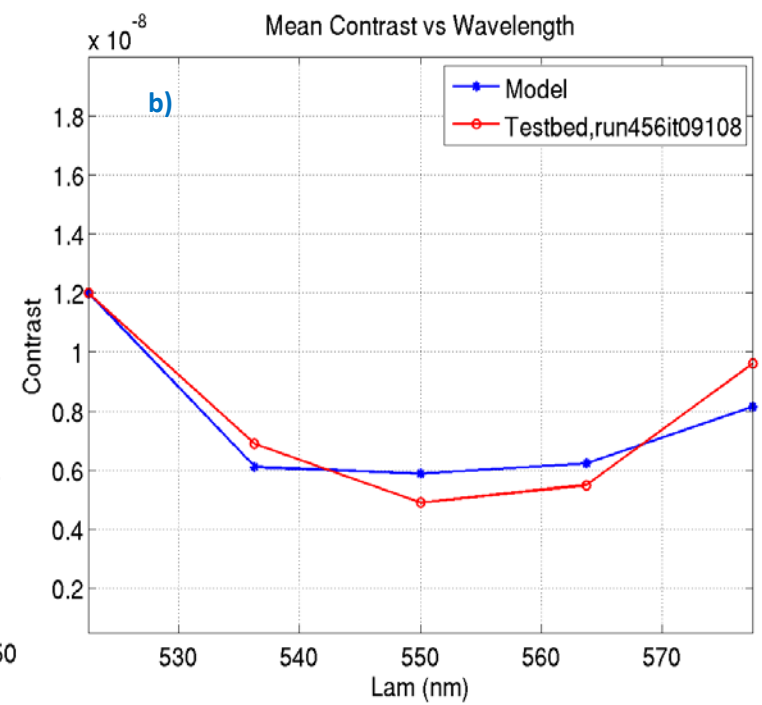
Significance of the Jacobian Error: EFC Modeling

- Adjusted prediction model Jacobian by the measured Jacobian error for each actuator:

$$G_{k,TB} = \frac{1}{1+pct_k} G_k \exp\left(\Delta\phi_x \cdot x + \Delta\phi_y \cdot y\right) \quad (5)$$

  - Actuator error exceeds 2σ, amp or phase, in error histogram remains unadjusted
  - Same Jacobian error for all λ
  - Estimated testbed WFE (~60nm rms total, w/ ~λ/10 RMS for focus and astigmatism)
- Closely matched testbed contrast behavior, in contrast floor, contrast chromaticity, contrast convergence, and EFC regularization
  - Jacobian amp error slows down convergence, while phase error sets the contrast floor

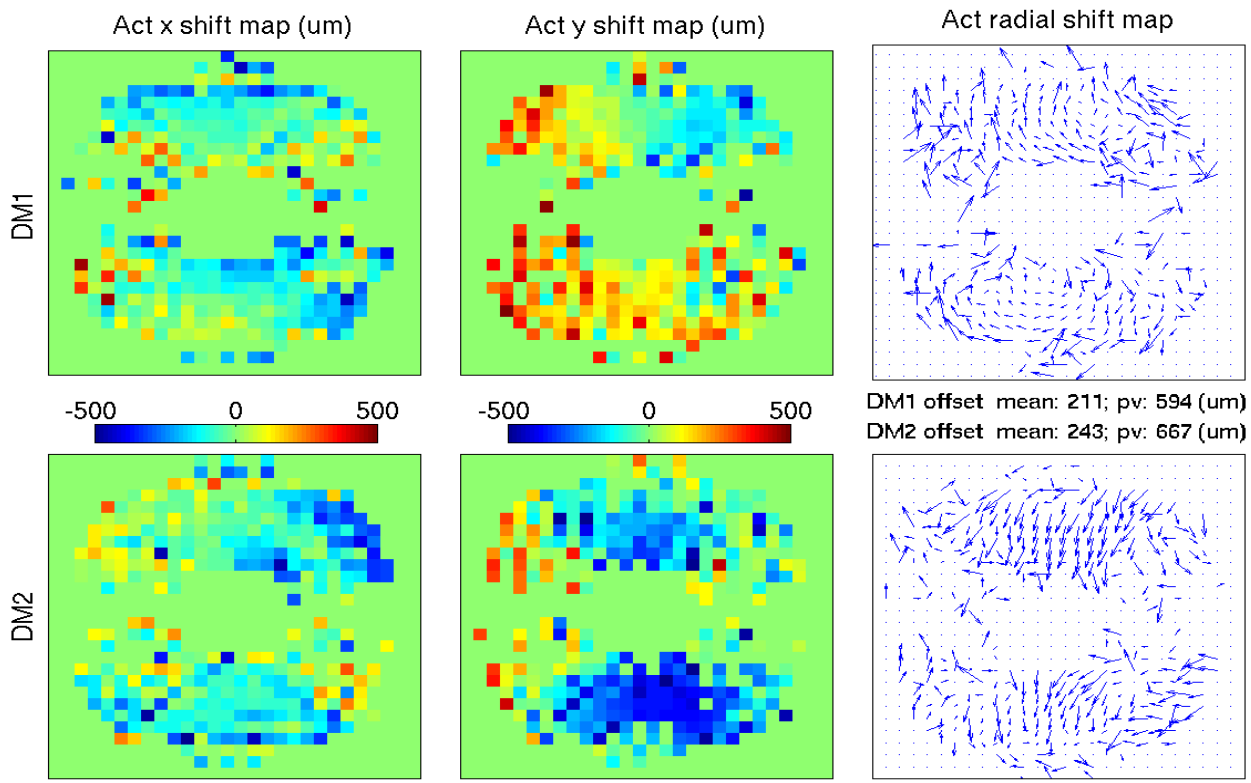




WFIRST Coronagraph

Sources for Jacobian Phase Error

- (Image space) phase error ➔ act registration error in DM space:
  act offset (rel to model) = $\lambda/2\pi \cdot \Delta\phi = \Delta tilt_{per_\lambda/D} * D/2\pi$
  - Mean (absolute, or radial) act registration offset (vs pupil) over ~200 um
  - Mean rigid DM misalignment by 5~15% actuator unit (50-150 µm)

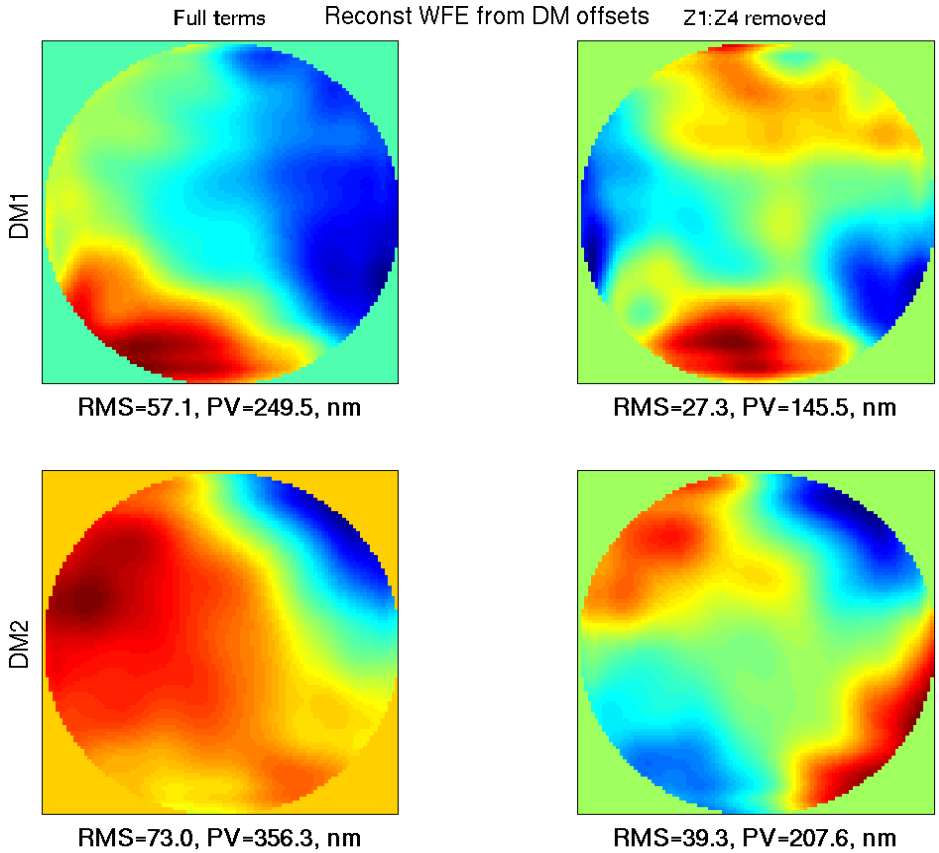


(X/Y shift maps orient up down wrt radial shift map)

outliers (>~2σ) removed

Reconstruct 'WFE' from DM Offsets

- Reconstruct 'WFE' from DM offsets (Shack-Hartmann method)
  - Reflects act grid distortion's impact on Jacobian E field phase modification
  - Tip/tilt error as result of misalignment of rigid DM vs pupil:
    - Thickness diff. after the reflective SPM replaced its surrogate flat, which was used for DM registration
  - Focus and astigmatism:
    - Unlikely due to actual physical actuator grid distortion
    - By system WFE and its DM setting? See next



Z2:Z6, in λ

-0.0748
0.0481
0.0200
-0.0164
-0.0371

- Both DMs show large mean shifts, some focus, and astigmatism

Z2:Z6, in λ

-0.0989
0.0349
-0.0391
0.0657
0.0128

- Different sign and direction of astigmatism

Sources for Jacobian Magnitude Error

- DM gain calibration check:
  1) Fixed small photometric normalization inconsistency
  2) Updated influence function (DM2)
  3) Discovered saturation & nonlinearity issue due to high poke in early data (~80nm piston) ; retook w/ smaller poke (~8nm)

- No fundamental improvement afterward

- Decided to check if system WFE and its DM setting has any effect

Sources for Jacobian Magnitude Error
Low-order WFE and its DM Setting on Jacobian

- Jacobian in presence of large WFE and its DM setting

$$G_k = C\left\{E_{pup}\exp\left[i\left(\varphi_{pup}+\phi_{dm,w}+\phi_{dm,k}\right)\right]\right\} - C\left\{E_{pup}\exp\left[i\left(\varphi_{pup}+\phi_{dm,w}\right)\right]\right\} \quad (6)$$

$$\approx C\left\{iE_{pup}\,\phi_{dm,k}\right\}$$

6a. Nominal Jacobian: w/ small WFE & poke, when linear approximation holds

$$\approx C\left\{iE_{pup}\,\phi_{dm,k} - E_{pup}\,\phi_{dm,k}\left(\varphi_{pup}+\phi_{dm,w}\right)\right\}$$

6b. Jacobian w/ Large WFE & DM setting

- E_{pup}: pupil E field; $\phi_{dm,k}$: *k*th act Jacobian poke; φ_{pup}: system WFE; $\phi_{dm,w}$: DM setting
- $\phi_{dm,w}$ would not fully cancel out φ_{pup} (EFC is to reshape, not to minimize WFE):
  - The (high order WFE) residual, $\varphi_{pup}+\phi_{dm,w}$, could reshape substantially during EFC
  - Also, inaccurate knowledge (in model) about WFE, φ_{pup}
- $\phi_{dm,k}$: approximate zero except the *k*th actuator being poked

- 2nd term of Eq. 6b adds a phase shifted copy of nominal Jacobian w/ an attenuated amplitude:
  - Attenuation proportional to the (high order) residual at *k*th act location: $\varphi_{pup}+\phi_{dm,w}$ (and inaccurate knowledge (in model) about WFE)

➔ Amplitude error and phase error relative to nominal Jacobian

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Jacobian Magnitude (and Phase) Error due to Large WFE and Its DM Setting

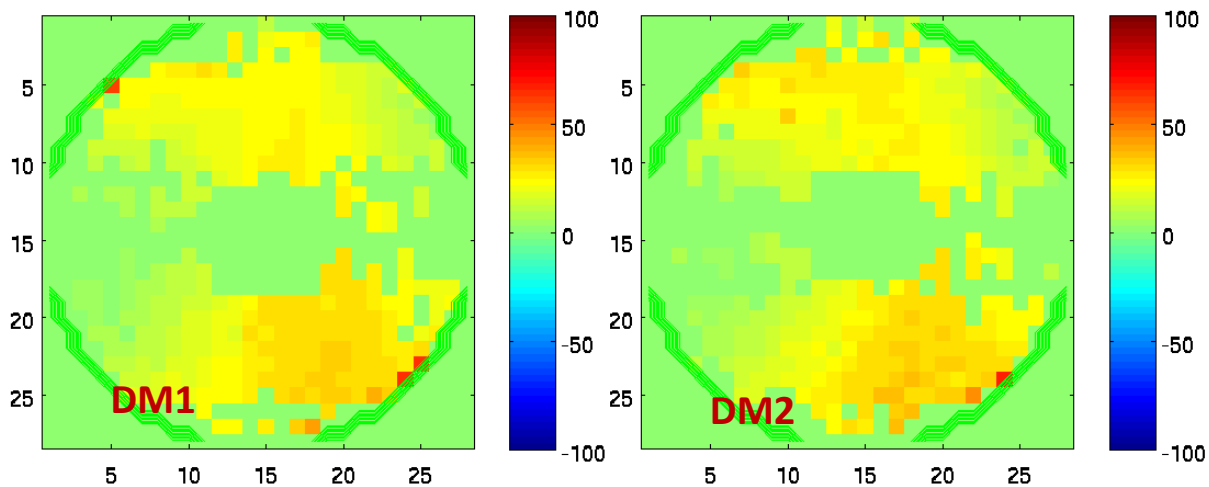
- Jacobian amplitude error (in %) relative to its nominal one:

$$err_{amp} \approx 100 * \left(\sqrt{1 + \left(\varphi_{pup} + \phi_{dm,w} \right)^2} - 1 \right) \quad (7)$$

- Jacobian phase will be modified by a term related to the residual:

$$err_{ph} \approx \varphi_{pup} + \phi_{dm,w} \quad (8)$$

- Compare nominal Jacobian and one w/ the estimated testbed WFE and its DM setting incorporated:
  - Zernike coeff *Z4-Z7* = [-45 -40 -10 2] nm rms, ~60nm rms total
  - ~20% amp increase on average ➔ significant <u>*relative to nominal Jacobian*</u>



- Amp. change (in %) is significant (20%) relative to nominal Jacobian for a moderate WFE (~60nm rms) and its DM setting

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Jacobian Magnitude (and Phase) Error due to Large WFE and Its DM Setting

- At the time of MS5, SPC testbed control Jacobian did not include WFE (but updated DM setting during EFC periodically) ➔ testbed control Jacobian error:
  - Amp error (in%):

$$err_{amp,TB} \approx 100 * \left(\sqrt{1+\varphi_{pup}^2} - 1 \right) \quad (9)$$

  - ➔ ~22% for testbed WFE: φ_{pup} = ~60nm rms, or 0.7 rad
  - **Closely matches the observed Jacobian amp error**

  - Jacobian Phase error:

$$err_{ph,TB} \approx -\varphi_{pup} \quad (10)$$

  - **Could be reflecting testbed WFE: both DMs Jacobian contain focus and astigmatism terms as WFE**

  - Magnitude and sign not match well (DM1)
  - Possible cause: bias error in measurement: phase component is model-derived
  - Need more work to fully understand

DM1 phase error Z2:Z6, in λ	DM2 phase error Z2:Z6, in λ	$-\varphi_{pup}$ -system W FE Z4:Z7, in λ
-0.0748	-0.0989	-
0.0481	0.0349	-
0.0200	-0.0391	0.0818
-0.0164	0.0657	0.0727
-0.0371	0.0128	0.0182
-	-	-0.0036

WFIRST Coronagraph

Summary

- Developed **a very useful tool** to diagnose testbed control Jacobian imperfections
- Analysis and modeling suggested **Jacobian error could be used to predict SPC testbed contrast performance**
  - Jacobian error appears to be limiting the contrast floor and affecting contrast convergence as observed on SPC testbed
- Two most **likely sources for the observed Jacobian error**:
  - Failure to include DM registration error (50~150 um rigid DM misalignment):
    ➔ Phase error
  - Failure to fully include WFE (or inaccurate WFE) and its DM setting when they were modestly large (~λ/10 rms)
    ➔ Magnitude error; possibly also for phase error
  - More works needed to fully explain the phase error
- For high contrast coronagraph, **Jacobian has a much tighter tolerance** on (knowledge of) imperfection

Future Work

- More works needed to fully explain the phase error
  - Possible cause: measurement bias (Jacobian phase component was model derived)
- Original SPC testbed decommissioned soon after Jacobian data taken
- Modifications to both testbed control model and prediction model are ongoing:
  - Control model: to include (& update if possible) WFE and its DM setting, DM misalignment error
  - Prediction model: to frequent/dynamic update Jacobian during EFC for large WFE case

Future work plan:

1. Repeat Jacobian survey and validate our method with data from new testbed
2. Incorporate Jacobian error back into control model (if unable to correct the error) and check on performance afterward
3. Potentially, use alternative phase estimation technique to minimize model-dependency caused bias error in Jacobian phase measurement