High Accuracy Coronagraph Flight WFC Model For WFIRST–CGI Raw Contrast Sensitivity Analysis

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CGI Flight WFC Model - Background

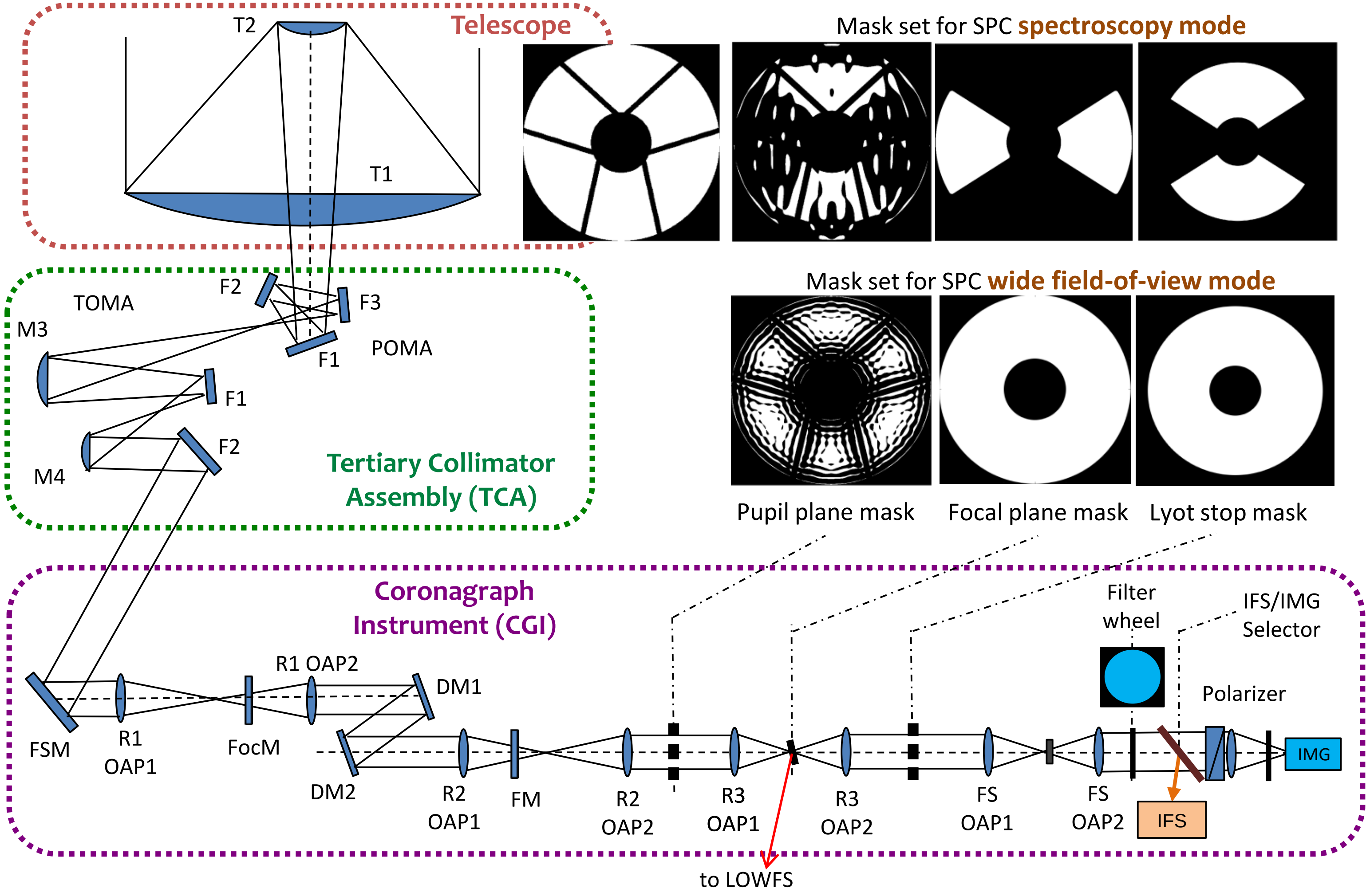
- WFIRST: Phase A ➔ Phase B; just recently completed project and CGI SRR/SDR
- CGI Performance requirements*:
  - **3 CGI modes**: 1) HLC narrow FoV imaging; 2) SPC wide FoV imaging; 3) SPC spectroscopy
  - **5 categories**: *throughput; **static contrast**; contrast stability; detector /noise; telescope interfaces*
- Raw contrast error budget needed to flow down requirements to subsystem levels

  No systematic study so far:
  - Usually not driving ***if*** assuming a very high raw contrast to start with
    - But for current CGI design: next most important metrics (along w/ stability) after throughput
  - Computationally demanding (long WFC iterations)
  - Difficult to accurately predict a real system's raw contrast until very recently**

> ➢ ***High accuracy flight WFC model for two CGI modes in support of CGI error budget process***

** Poberezhshiy, I., et al, this conference Proc.*
*** H. Zhou. et al., Proc. SPIE 10400 (2017)*

WFIRST - CGI Schematic / SPC Modes Masks



- 2016030 cycle 6 telescope pupil
- 20170714 flight design **spectroscopy** mode*
  18% BW, band 3 (760nm λ_o)
- 20170130 flight design **wide FoV** mode*
  10% BW, band 4 (825nm λ_o)

*AJ Riggs et al, Proc SPIE 10400 (2017)

- ***30+ optical elements involved in current optics layout (excluding LOWFS and IFS arm optics)***

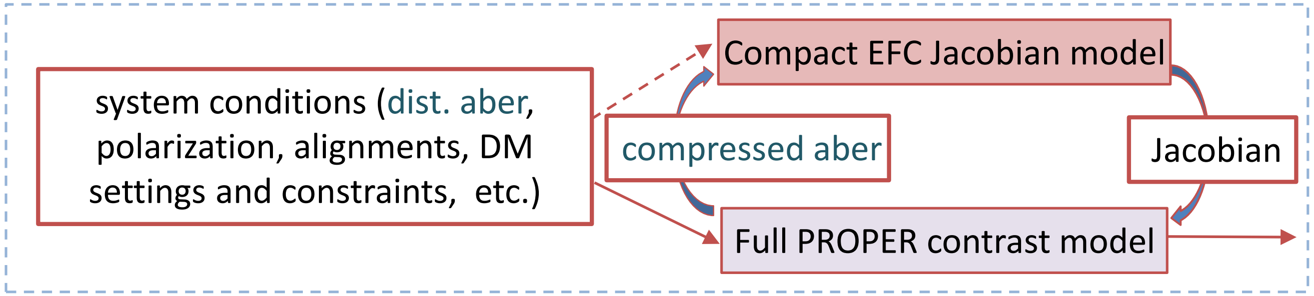
CGI Flight WFC Model: Baseline Configuration

Goal: ***realistic*** in representation of flight system's aberrations and constraints; ***accurate*** in error sensitivity assessment; and capable of ***individual error*** item evaluation as desired

- Flight WFC model = ***full PROPER contrast model* + compact EFC Jacobian/control model***:

  (Fresnel prop; full mask sizes, high FFT padding; For ***high accuracy*** contrast evaluation)

  (FFT prop mostly; reduced mask sizes, low FFT padding; For Jacobian calc w/ *limited on-board flight processor*)



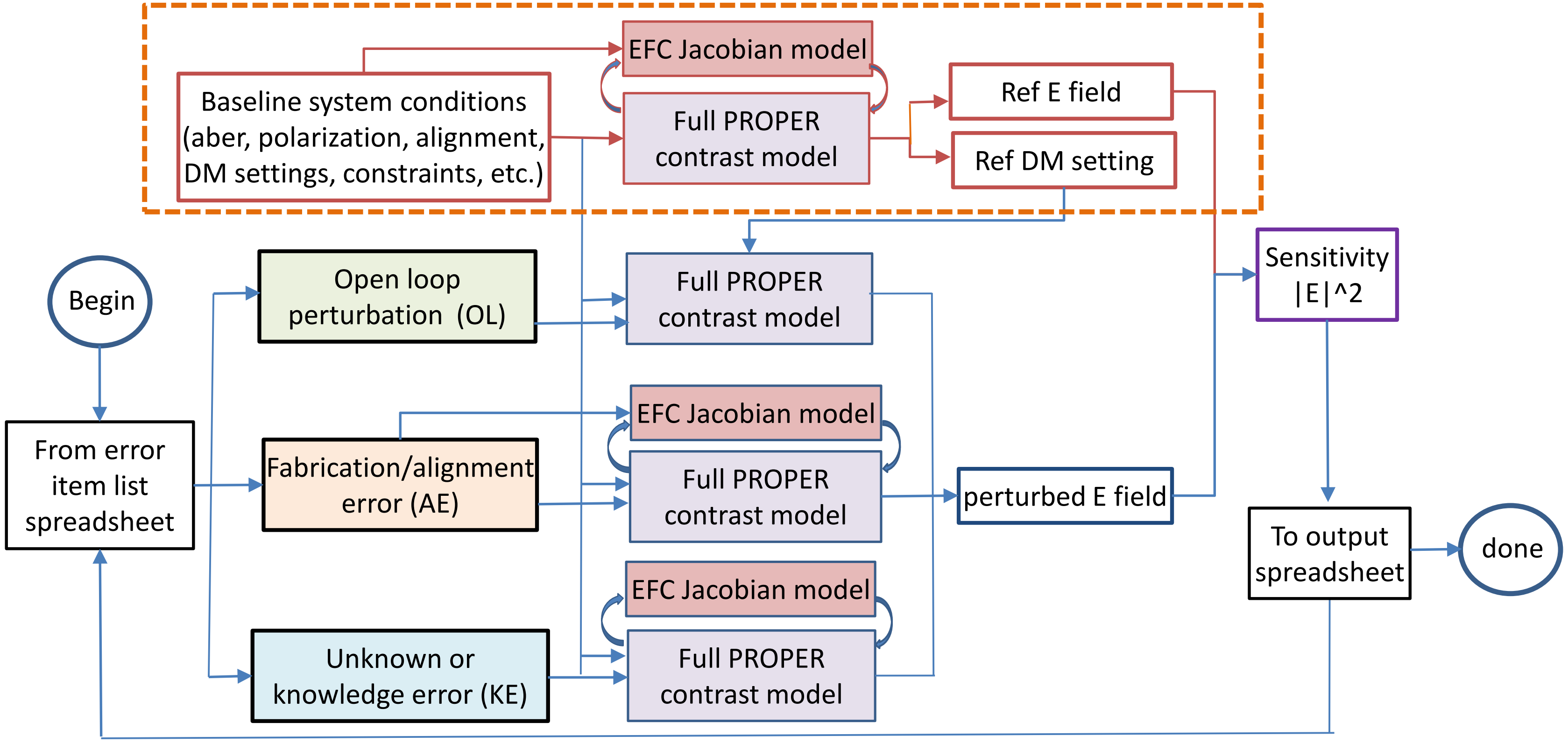
- Standard image-plane based WFC algorithm (EFC**)
- Unpolarized incoming light with no polarizer (for both of CGI modes evaluated here)
  - Contrast evaluation: incoherent sum of 4 channel intensity images: X's & Y's of both +/-45^{o} input
  - Electric field evaluation: simple mean of the four polarization aberration maps

** J. Krist, Proc. SPIE 10400 (2017); aberration includes optics figure & low-order WFE at FSM for telescope alignment error*

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

SPC Flight WFC Model: Automated Evaluation

- Read from /write to spreadsheet files
- Two of three CGI modes: ***Spectroscopy mode*** and ***wide FoV imaging mode***
- Three types of error:
  - ***Open loop perturbation***: only contrast model involved (no EFC)
  - ***Fabrication /Alignment error*** (Known imperfection): error incorporated in both contrast & Jacobian models
  - ***Calibration error*** (Knowledge error): error in contrast model but not Jacobian model



List of Error Items, Types, and Typical Quantities

Category	Error Names	Typical Qty	Numbers & Types of eval
Telescope Interface	Pupil (edge) clocking	0.1 deg	3; OAK
	Pupil (edge) lateral shear	0.1%D	6; OAK in x and y
	Beam (wavefront) clocking	0.1%D	3; OAK
	Beam (wavefront) shear	0.1deg	2; O, in x and y
	Strut width	0.1%D	3, OAK
	Pupil magnification	1%D	3; OAK
	Secondary mirror diam	1%D	3; OAK
	Pointing / source lateral offset	0.1 λ/D	6; OAK; in x and y
Optical Misalignment or Mismatch	Deformable mirror tip/tilt/clocking	[0.5 0.5 0.1] deg	18; OAK; DM1, DM2
	Deformable mirror lateral and axial offset	[10 10 1000] um	14; OAK; DM1, DM2
	Shaped pupil mask tip/tilt/clocking	[0.5 0.5 0.1] deg	9; OAK;
	Shaped pupil mask lateral and axial offset	[10 10 10] um	9; OAK; in x,y, and z
	Focal-plane mask tip/tilt/clocking	[0.5 0.5 0.1] deg	9; OAK;
	Focal-plane mask lateral and axial offset	[10 10 10] um	9; OAK; in x,y, and z
	Lyot tip/tilt/clocking	[0.5 0.5 0.1] deg	9; OAK;
	Lyot lateral and axial offset	[10 10 10] um	9; OAK; in x,y, and z
	Beam magnification at focal-plane mask	1%	3; OAK
	Beam magnification at shaped pupil	1%	3; OAK
	Beam magnification at Lyot stop	1%	3; OAK
Component Fabrication or Usage	Shaped pupil mask undercut	1%	1; K
	Focal-plane mask inner, outer radius	1um	2; K;
	Focal-plane mask angle extend & offset	[0.5 0.5]deg	2; A;
	Lyot stop inner, outer radius	1um	2; K;
	Shaped pupil mask magnification	1%	1; A
	Shaped pupil mask surface WFE	1nm	1: A
	Deformable mirror actuator gain	5%	1;K
	Deformable mirror quantization	16 bit DAC	1; K
	Deformable mirror thermal offset	10 mk	1; OK
System Aberrations	Achromatic wavefront error Z2~Z4, at fast-steering mirror	1nm	3; O
	Chromatic wavefront error Z2~Z6, at fast-steering mirror	+/- 1nm	15; OAK
	Achromatic amplitude error Z2~Z6+, at DM1	1%	18; OAK
	Chromatic amplitude error Z2~Z6+, at DM1	+/-1%	18; OAK
	wavefront error at DM1, Z4~Z8+	1nm	18; OAK
	wavefront error at shaped pupil, Z4~Z8+	1nm	18; OAK
	wavefront error at Lyot stop, Z4~Z8+	1nm	6; O
Algorithm	Plate scale	0.05 λ/D	1; K
			Total: ~ 233

O: open loop
A: Alignment error, CL
K: knowledge error, CL

- 90+ distinct items
- 230+ total items for spectroscopy mode
  - 1, 2, or all 3 error types (O, A, K)
- 100 items for wide FoV mode
  - O or A or both

Baseline Raw Contrasts

- Baseline raw contrasts (modulated)

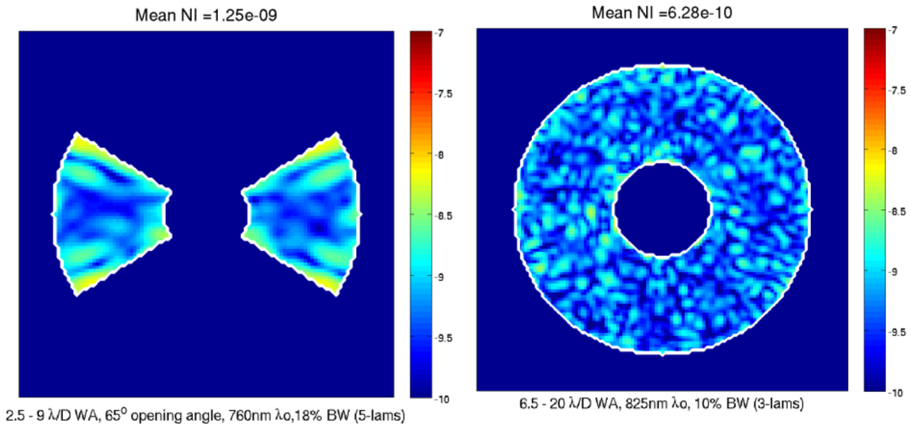
CGI modes	band & bandwidth	DH region	ideal design	aberrated	post flatten	post EFC
spectroscopy	band 3 (760nm), 18%	2.5 ~9λ/D	2.06E-09	4.4E-04	2.3E-06	1.3E-09
wide FoV imaging	band 4 (825nm), 10%	6.5 ~20λ/D	8.00E-10	4.3E-05	1.7E-06	6.3E-10

x MUF 2 ➔“design contrast”

- Imperfect Jacobian (due to economical size of compact EFC model)
  - Compared to a full-sized compact EFC model:

    Relative mean mag errors 7% & 15% for DM1 & DM2;
    Skewed by a few extreme actuator outliers at edges
  - Minor impact on final contrast floor

    1.25e-9 vs 1.21 e-9 (economical vs full size compact)



➢ Expect to meet flight processor constraints

Observations and Discussions - 1

1. Phase A flight vs “HCIT Flight”

(Spectroscopy mode)

- Generally improved sensitivities than past*

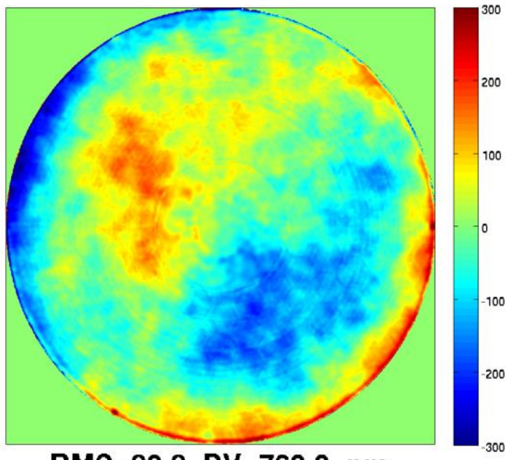
  Better design, smaller system aberrations

- More sensitive to chromatic WFE, and pupil /SPM clocking
  - Use no polarizer for SPC modes (to boost throughput)
  - Large PM/SM optics has larger edge WFE than OTA simulator

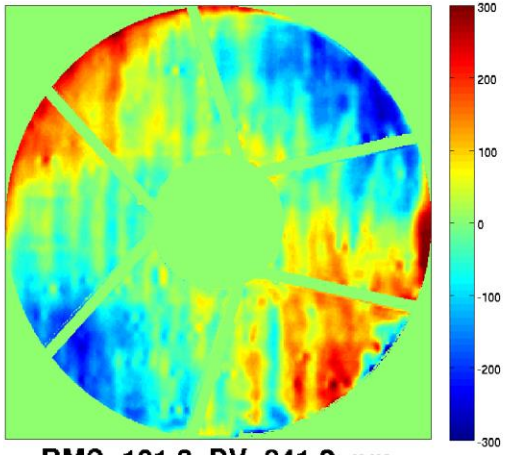
➢ Impact of different aberration characteristics

- Poberezhshiy, I., et al, AAS #231, ID # 355.14 , 2018

Phase A flight aberration



RMS=89.8, PV=760.0, nm



RMS=101.3, PV=841.2, nm

HCIT Flight aberration

Observations and Discussions - 2

2. Spectroscopy mode vs wide FoV mode

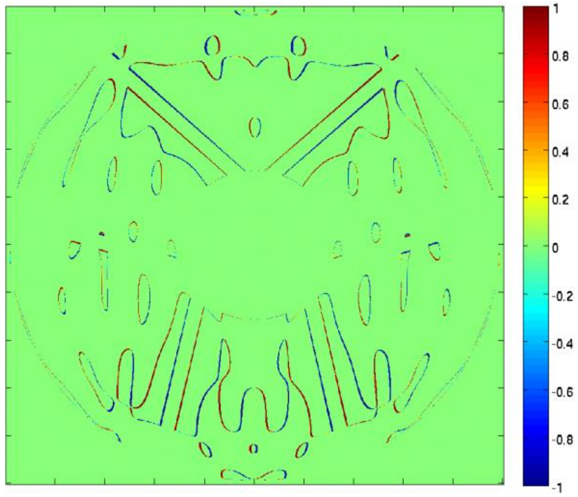
- **Spectroscopy:** ***chromatic WFE*** main contrast floor setting; followed by SPM clocking, etc.
- **Wide FoV**: more susceptible to ***SPM related errors***: clocking, undercut, mask/beam size mismatch

3. Known errors vs Unknown errors

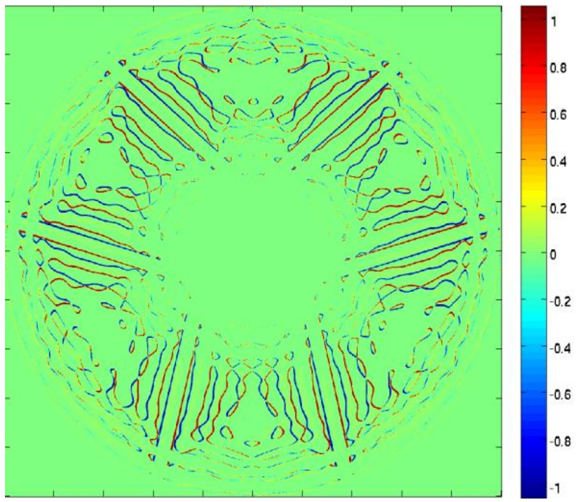
- ***Not much different***: EFC compensates out small error?
- Small error added on top of a perfectly known model w/ baseline conditions
- In real system, many unknowns coexist (or a single large unknown as sometimes on the testbed): behavior may change

- Poberezhshiy, I., et al, AAS #231, ID # 355.14 , 2018

Clocking error by spectroscopy mask



Clocking error by wide FoV imaging mask



Observations and Discussions - 3

4. Full ***contrast*** model vs compact ***contrast*** model

- Full model: ability to evaluate individual error terms

  Optical axial position accuracy for DMs, SPM, Occulter mask, and Lyot Stop mask, etc.

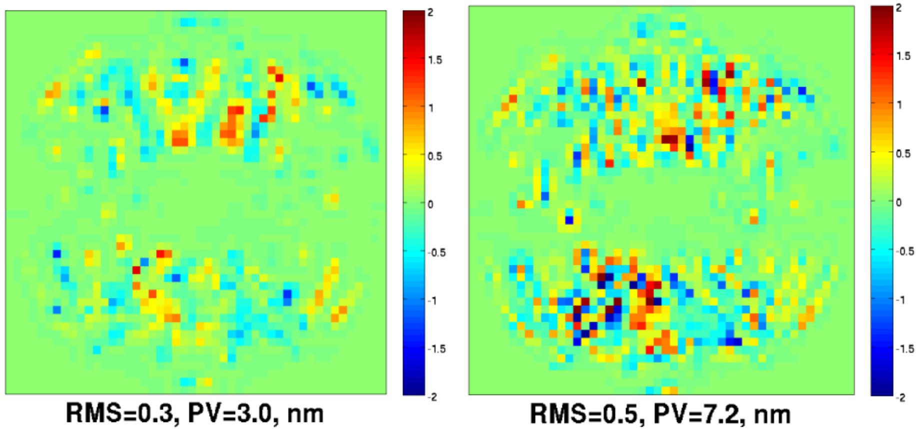
- Better accuracy for certain location dependent error sensitivities, e.g.

  Compact model OL sensitivity: ➡
  i. ***overestimate*** beam (wavefront) shear by ~4x
  ii. ***underestimate*** pupil (edge) shear by ~5x

  In full model: ➡
  i. distributed WFE among optics and less severe up to FSM plane
  ii. cascading effect of diffraction (at telescope strut) at the front of telescope

- Same Jacobian, different dark hole DM solutions
  - Interchange post EFC DM settings from /to full /compact models: ➔ ***huge contrast difference****: from 1.25e-9 to 1e-6; or 1.32e-9 to 9.3e-7
  - ❖ *On testbed: the measured raw contrast way better than its control model predication*

➢ *Testbed EFC process is more ~ [a full contrast model + a compact Jacobian model], than [a compact one for both]*



Difference between dark hole DM solutions of full contrast model and of compact contrast model

Error Sensitivity Tall Tentpoles: Spectroscopy

- Chromatic aberrations, SP mask positioning, size mismatch, and focal plane mask clocking have the most impact on contrast floor
  - Similar impact whether it's KE or AE

Error Names	Qty		3-4 l/D	4-5 l/D	5-8 l/D		avg
Close Loop (KE,AE)							
chromatic WFE Z4	+/-1nm		3.90E-10	1.20E-10	1.90E-10		2.30E-10
chromatic WFE Z5	+/-1nm		7.30E-11	3.30E-11	6.00E-11		5.50E-11
chromatic WFE Z6	+/-1nm		2.90E-11	1.10E-11	2.50E-11		2.20E-11
chromatic amp Z4	+/-1%		2.90E-10	9.50E-11	1.40E-10		1.80E-10
chromatic amp Z5	+/-1%		7.90E-11	3.10E-11	7.90E-11		6.30E-11
chromatic amp Z6	+/-1%		9.10E-11	5.10E-11	7.80E-11		7.40E-11
chromatic amp> Z6	+/-1%		4.50E-09	1.10E-09	2.00E-09		2.50E-09
sp clocking	0.5deg		1.60E-10	1.60E-10	5.10E-10		2.80E-10
sp xtilt	0.5deg		4.90E-11	4.00E-11	9.00E-11		6.00E-11
sp mag	0.50%		1.10E-11	1.60E-11	2.20E-11		1.60E-11
bt clocking	0.5deg		1.10E-11	1.10E-11	5.20E-11		2.50E-11
beam mag at sp	0.50%		1.45E-11	1.50E-11	1.90E-11		1.60E-11
DM quantization	16 bitDAC		1.10E-11	9.90E-12	1.70E-11		1.30E-11

Error Sensitivity Tall Tentpoles: Wide FoV Imaging

Less sensitive than spectroscopy mode in general, except:

- SP mask related items, have the most impact → tighter requirement than IFS case
- Beam size match to masks

Error Names	Qty		3-4 l/D	4-5 l/D	5-8 l/D		avg
Close Loop (KE)							
Beam mag bt	0.50%		1.04E-10	3.51E-11	1.37E-10		9.2E-11
beam mag sp	0.50%		2.64E-10	1.24E-10	2.15E-10		2.01E-10
beam mag ls	0.50%		6.04E-11	2.54E-11	2.54E-11		5.63E-11
pup mag	1% ofD		1.71E-11	1.56E-11	1.54E-11		1.6E-11
sp clocking	0.5deg		9.47E-10	7.65E-10	9.67E-10		8.93E-10
sp undercut	1%		1.49E-09	3.57E-10	6.71E-10		8.4E-10
chrm amp dm1 gt Z6	1%		3.88E-10	1.4E-11	1.31E-11		1.38E-10

Raw Contrast Error Budget Breakdown

5. Error budget breakdown example (spectroscopy mode)
   - Coherent contrast – main subject of this work:
     - **design contrast** w/ baseline system conditions
     - contributions from errors (linearly summed up): **misalignment/fabrication**; **miscalibration**
   - Incoherent contributions: OL or aggregated OL sensitivities
     - **static incoherent**: stellar size, stray light, zodi, polarization, estimation, etc.
     - **dynamic incoherent**: jitters – tip, tilt, focus, high order, pupil shear, etc.

section contrast rollup

Level C		**Allocation**		**Sensitivity**							**Contrast**		
Misalignment and fabrication											4.23E-09	1.83E-09	2.94E-09
					3-4 L/D	4-5 L/D	5-8 L/D	per	[unit]				
	Mask alignment relative to nominal				**ROLLUP**						**1.49E-10**	**1.33E-10**	**3.13E-10**
	shaped pupil mask X	10	um	1	9.94E-13	1.03E-12	2.36E-12	10.00	um	2	1.99E-12	2.06E-12	4.71E-12
	shaped pupil mask Y	10	um	1	9.18E-13	1.25E-12	2.43E-12	10.00	um	2	1.84E-12	2.50E-12	4.86E-12
	shaped pupil mask Z	100	um	1	4.02E-15	4.01E-15	1.01E-14	10.00	um	2	8.04E-13	8.02E-13	2.03E-12
	shaped pupil mask clocking	0.1	deg	1	1.15E-10	1.19E-10	3.67E-10	0.50	deg	2	9.23E-12	9.50E-12	2.93E-11
	shaped pupil mask tip	0.5	deg	1	4.90E-11	4.00E-11	9.00E-11	0.50	deg	2	9.80E-11	8.00E-11	1.80E-10
	shaped pupil mask tilt	0.5	deg	1	1.70E-14	2.21E-14	8.65E-14	0.50	deg	2	3.40E-14	4.42E-14	1.73E-13

error sources identified

allocation

sensitivity calculated per unit indicated

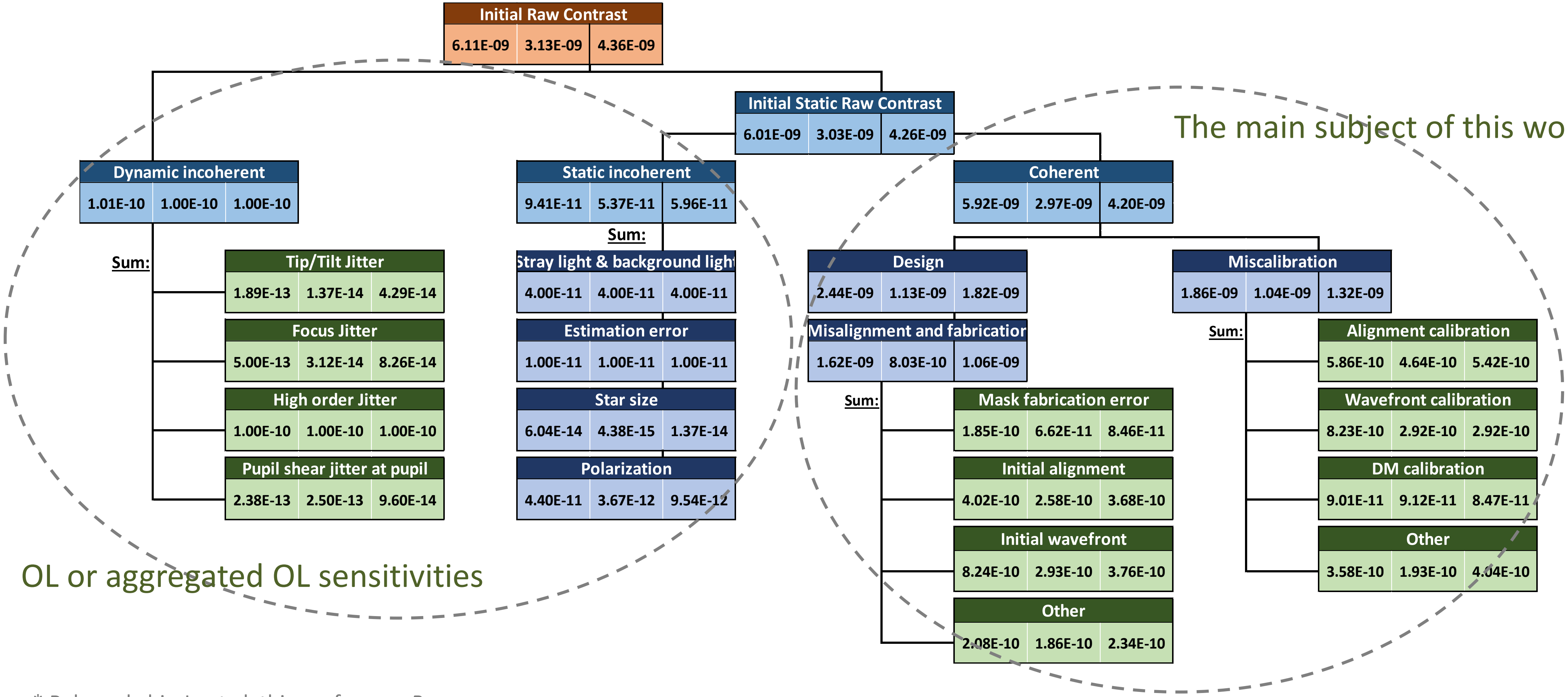
MUF

estimated contribution per allocated

* Poberezhshiy, I., et al, this conference *Proc.*

Raw Contrast Error Budget Tree

5. Raw contrast error budget tree, wide field-of-view mode



* Poberezhshiy, I., et al, this conference *Proc.*

Summary and Future Plan

Summary:

- Developed high accuracy flight WFC model for ***CGI raw contrast error budget flow down***
  - Combination of a ***Full PROPER contrast model + compact Jacobian model***
  - ➢ *Better reflection of a real system's EFC process*
- **90+ error items** identified and evaluated w/ automated process

  For **two CGI modes**, **three error types:**
  - Generally improved sensitivities compared to previous generation of mask design
    - **Spectroscopy** mode: chromatic WFE, shaped pupil mask errors among top contributors
    - **Wide FoV** mode: shaped pupil mask errors
  - Calibration errors have similar impact as known imperfections at the small level evaluated
  - Full contrast model desired while economical control/Jacobian model adequate
  - Forms the basis for CGI error budget flow down to the subsystem level

Future works:

- Rerun for Phase B new design (for changed telescope pupil)
- Modify for any new baseline WFC strategy
- Include any emerging new error items as needed

BACKUP SLIDES

Waveofrnt Sensing and Control Algorithm

Image–plane based electric field conjugation (EFC) algorithm*

- To sense, use pair-wise DM probing*

$$I_j^{+/-} = \left|E \pm \Delta P_j\right|^2 + I_{inc} = \left|E\right|^2 + \left|\Delta P_j\right|^2 \pm 2\,\Re\left\{E^* \Delta P_j\right\} + I_{inc} \qquad (1)$$

$$\Delta I_j \equiv I_j^+ - I_j^- = 4\Re\left\{E \Delta P_j\right\} \qquad (2)$$

ΔP_j: probing field, obtained by propagating DM probe patterns through the coronagraph model

- To control, actuator adjustment at each iterations:

$$\Delta h = \left[\, J^T J + 10^{\beta} \cdot \max\left(diag\left(J^T J\right)\right) I \,\right]^{-1} J^T E \qquad (3)$$

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

Implementation Notes

- **Mask lateral shift:** This includes shaped pupil, focal-plane, and Lyot stop masks. Apply equivalent tilt in FT domain, multiply the mask, FFT back, then remove the tilt out (applying a negative tilt).
- **Shaped pupil mask clocking and magnification:** FFT a 4× zero-padded mask, rotate or magnify it in the Fourier domain (more smooth rotation / magnification), and then FFT back.
- **Shaped pupil undercut:** For each non-interior pixel, we assign a reflection magnitude drop (rel. to 1) based on how much area it lost for a specified amount of undercut from an overetch during black-silicon processing. The loss in area depends on how many open neighbors it has and the locations of the undercut sides.
- **Beam magnification and mask magnification (mismatch):** the former refers to the incorrect beam size than expected (e.g., from misaligned optics) but mask is correctly manufactured; the latter refers to correct beam size but incorrectly manufactured mask size.
- **Telescope pupil/beam lateral shear:** The former (mask edge) is shifted upfront in model at the telescope entrance pupil by using a pupil drawing tool to give precise shift. For the beam shear, we shift wavefront loaded beam laterally at the FSM plane, simulating a possible beam walk due to telescope pointing or telescope - CGI interface breakup where telescope itself is treated as a rigid body.
- **DM registration, gain, and voltage constraints:** When there is knowledge error (i.e., “unknown”) in calibration of DM registration, gain, or just apply the voltage constraints, they become “known” even if the errors are labeled as knowledge error. This is because iterative DM flattening process implicitly “works out” these errors. The unknown error should only be applied to the subsequent EFC portion of DM.
- **Aberrations for compact control model:** both known and unknown aberration errors are effectively “known” through the flattening process and are then fed to compact control model through estimation procedure.

SPC Flight WFC Model: Automated Evaluation

Category	Type	Name	Short name	size	units
Telescope pupil	Alignment	Strut width change	strut width	0.1	% of tel D
Polarization	Knowledge	rms delta Z4 from system polarization (+/- to ends of band)	chrm wfe Z4	1	nm
Telescope pupil	Knowledge	Strut width change	strut width	0.1	% of tel D
Polarization	Open-loop	rms delta Z2 from system polarization (+/- to ends of band)	chrm wfe Z2	1	nm
Polarization	Open-loop	rms delta Z3 from system polarization (+/- to ends of band)	chrm wfe Z3	1	nm
Polarization	Open-loop	rms delta Z5 from system polarization (+/- to ends of band)	chrm wfe Z5	1	nm
Polarization	Open-loop	rms delta Z6 from system polarization (+/- to ends of band)	chrm wfe Z6	1	nm
Starting system wavefront	Open-loop	rms Z2 at FSM	pup wfe Z2	1	nm
Starting system wavefront	Open-loop	rms Z3 at FSM	pup wfe Z3	1	nm
Starting system wavefront	Open-loop	rms Z4 at FSM	pup wfe Z4	1	nm
Starting system wavefront	Open-loop	rms Z5 at FSM	pup wfe Z5	1	nm
Telescope pupil	Open-loop	Pupil clocking (edge only, no WF)	pup clocking	0.1	deg
Telescope pupil	Open-loop	Pupil shear X (edge only, no WF)	pup xshear	0.1	% of tel D
Telescope pupil	Open-loop	Pupil shear y (edge only, no WF)	pup yshear	0.1	% of tel D
Telescope pupil	Open-loop	WF clock	beam clocking	0.01	deg
Telescope pupil	Open-loop	WF shear X	beam xshear	0.1	% of tel D
Telescope pupil	Open-loop	WF shear Y	beam yshear	0.1	% of tel D
Polarization	Open-loop	rms delta Z4 from system polarization (+/- to ends of band)	chrm wfe Z4	1	nm
Mask alignment relative to nom	Alignment	shaped pupil mask X	sp xshift	10	um
Mask alignment relative to nom	Alignment	shaped pupil mask Y	sp yshift	10	um
Algorithm calibration	Knowledge	Plate scale	plate scale	0.05	L/D
DM actuator calibration	Knowledge	DM gain calibration uncertainty	dm dgain	5	%

Wide FoV Imaging: OL Error Sensitivity Tall Tentpoles

Among so far evaluated:

- Mostly pupil/beam mismatch (clocking, shearing, etc)

Error Names	Qty		3-4 l/D	4-5 l/D	5-8 l/D		avg
Open Loop							
pup clocking	0.1 deg		3.9E-10	5.46E-10	2.43E-10		3.93E-10
pup xshear	0.1%D		7.06E-10	9.07E-10	3.77E-10		6.63E-10
pup yshear	0.1%D		8.65E-10	1.11E-09	5.43E-10		8.38E-10
beam clocking	0.1deg		4.62E-08	3.98E-08	1.62E-08		3.41E-08
beam xshear	0.1%D		1.98E-08	2.32E-08	9.19E-09		1.74E-08
beam yshear	0.1%D		3.12E-08	3.03E-08	1.14E-08		2.43E-08
dm1 clocking	0.1 deg		5.02E-08	3.66E-08	1.72E-08		3.47E-08
dm2 clocking	0.1deg		3.49E-09	8.31E-09	4.09E-09		5.3E-09
beam mag sp	0.10%		3.72E-09	2.19E-09	1.39E-09		2.43E-09
pup wfe dm1 gt Z8	1nm		6.06E-09	2.06E-10	1.43E-10		2.14E-09