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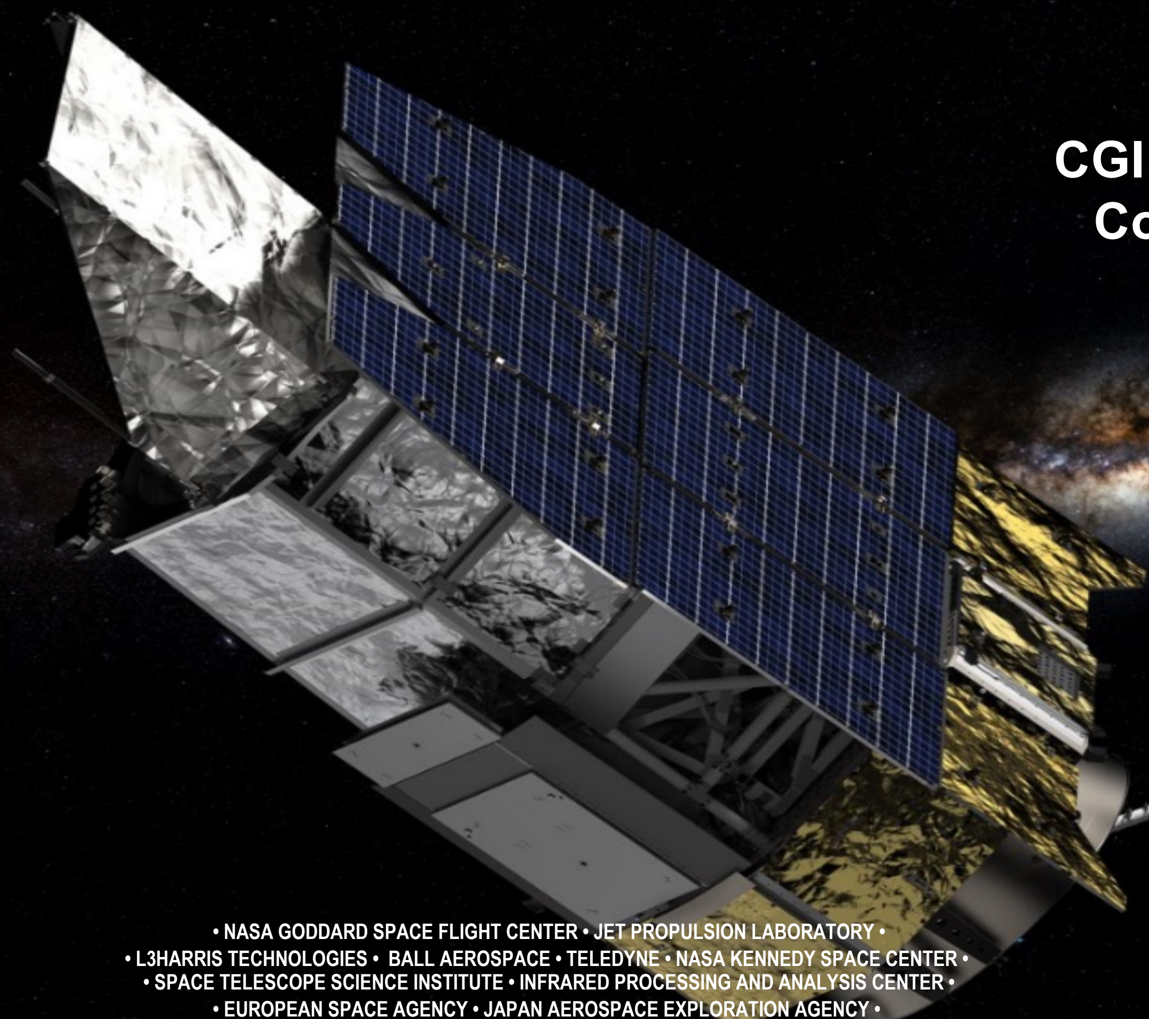
CGI High-Order Wavefront Sensing and Control (HOWFSC) Architecture and Results Summary



Eric Cady for the CGI team

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Pasadena, CA 91109

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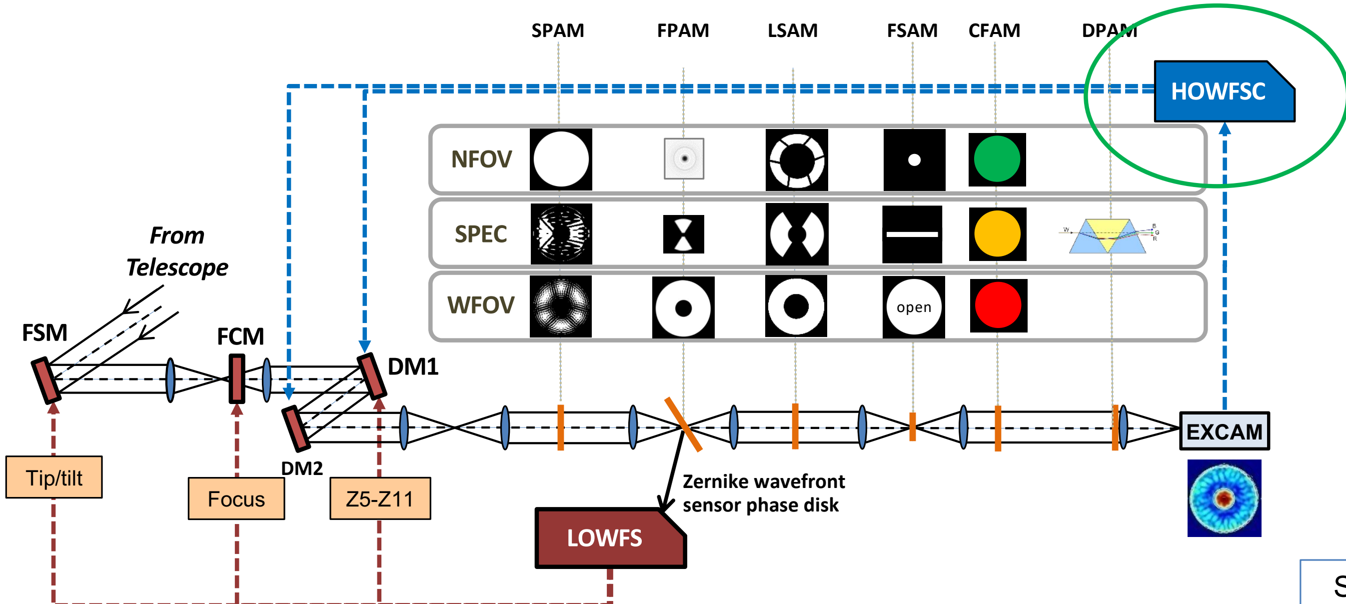
HOWFSC architecture

What is HOWFSC?



TTR5: (Technology Demonstration Requirement at Level 1)
Roman shall be able to measure (using CGI), with SNR ≥ 5, the brightness of an astrophysical point source located between 6 and 9 λ/D from an adjacent star with a V_AB magnitude ≤ 5, with a flux ratio $\geq 1\cdot10^{-7}$; the bandpass shall have a central wavelength ≤ 600 nm and a bandwidth ≥ 10%.

Decompose via error budget

Static coherent raw contrast 6-9 λ/D: ≤ 5e-8
Static incoherent raw contrast 6-9 λ/D: ≤ 1e-7
(goals 3-9 λ/D with HLC, 3-20 λ/D over all)

CGI high-order wavefront sensing and control (HOWFSC):

- measures electric fields at the science focal-plane
- uses that information, along with a model of the system, to adjust the DMs to minimize residual starlight in focal-plane regions of interest ("dark hole")

Necessary to meet our contrast requirements! Can't get dark enough with good alignment + good optics

Wavefront estimation (pairwise probing)

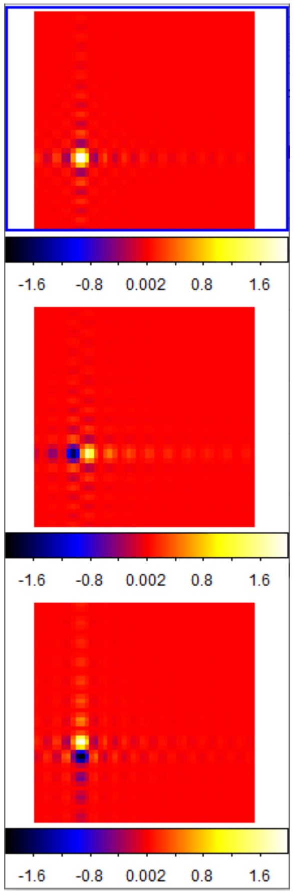
For correction, we need to know the complex image-plane electric field ($A(x,y)e^{i\phi(x,y)}$) from starlight.

- What we actually have is the intensity ($|A(x,y)|^2$) added on top of intensities from other sources ("incoherent light", e.g. planets/disks/exozodi, stray light, ghosts and other unusable starlight) for a total intensity of $|A(x,y)|^2 + I_{inc}(x,y)$.

Solution: use a set of positive and negative *probes*—small DM settings in the pupil—to modulate the wavefront and take images. [Give'on, Kern, and Shaklan 2011]

- We use pairs to simplify the estimation of the probe amplitude.
- Get probe phase from optical model (not measured directly)
- Minimum of five images (2 pairs + unprobed) for five independent variables
  - CGI uses seven images (3 pairs + unprobed) to avoid noise-induced ill-conditioning on 2x2 inversion, and to compensate for areas of low modulation

Get final $I_{inc}(x,y)$ by subtracting $|A(x,y)|^2$ from an unprobed image.



Wavefront control (electric-field conjugation)

Basic EFC approach (Give'on et al. 2007): assume the field near the current position can be modeled as:

$$E_1(x, y) \approx E_0(x, y) + \sum_n a_n J_n(x, y)$$

for DM actuator settings *a*, and solve for *a* to minimize

$$\left\| E_0(x, y) + \sum_n a_n J_n(x, y) \right\|_2$$

In practice we discretize to get

$$\|E + Ja\|_2$$

and solve an *Ax* = *b* equation as solution to least-squares problem with standard linear-algebra tools.

CGI extensions to this:

- Use weightings (W_E) on pixels to remove dead pixels, emphasize regions
- Use weightings on actuators (W_{DM}) to capture dead or tied actuators
- *E* will include pixels from several different wavelengths to capture chromatic variation
- Add a regularization term (λ) to balance model (*J*) vs data (*E*)
  - "Control strategy" can change these weights and regularizations per iteration
  - Use regularization scheduling to "ratchet" to higher contrast (see Cady et al. 2017, Seo et al. 2017, Marx et al. 2017)

$$A = W_{DM}^T J^T W_E^T W_E J W_{DM} + \lambda I$$
$$B = W_{DM}^T J^T W_E^T E_0$$

Final CGI tweak: minimize intensity *relative to PSF peak* ("normalized" intensity) rather than just intensity to keep the PSF sharp (see Section 3.3 of Llop-Sayson et al. 2022)

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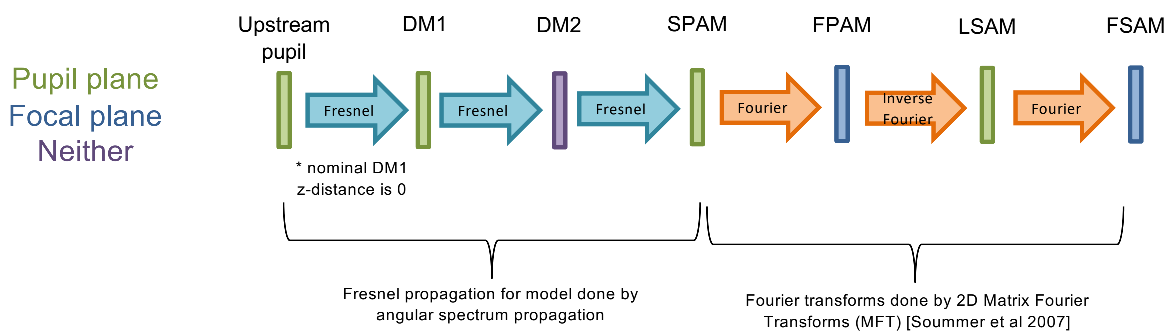
HOWFSC optical model

ROMAN CORONAGRAPH

We use an optical model of CGI, simplified for HOWFSC relative to high-fidelity model from Integrated Modeling, to:

- calculate probe phases (wavefront estimation)
- calculate Jacobians (wavefront correction)
- calculate contrast estimates for the next iteration (operator monitoring, camera-settings calculation)



Dedicated data collection activities and ground software (GSW) tools used to build the optical model from a combination of measured data and design specifications.

The primary reason HOWFSC will slow or stop at moderate contrasts is model mismatch!

Ground-in-the-loop (GITL)

Until late 2019, HOWFSC was planned to be done entirely onboard in FSW

- Separate dedicated copy of CGI processing board in hardware (SSP)
  - Active work to accelerate Jacobian and model calculation via attached RTG4 FPGA and integrate calculation periods into ops, as computation timing did not close otherwise
  - Also used board for calibrations (e.g. phase retrieval)
- Dedicated solid-state recorder (SSR) for Jacobian storage (tens of GB)

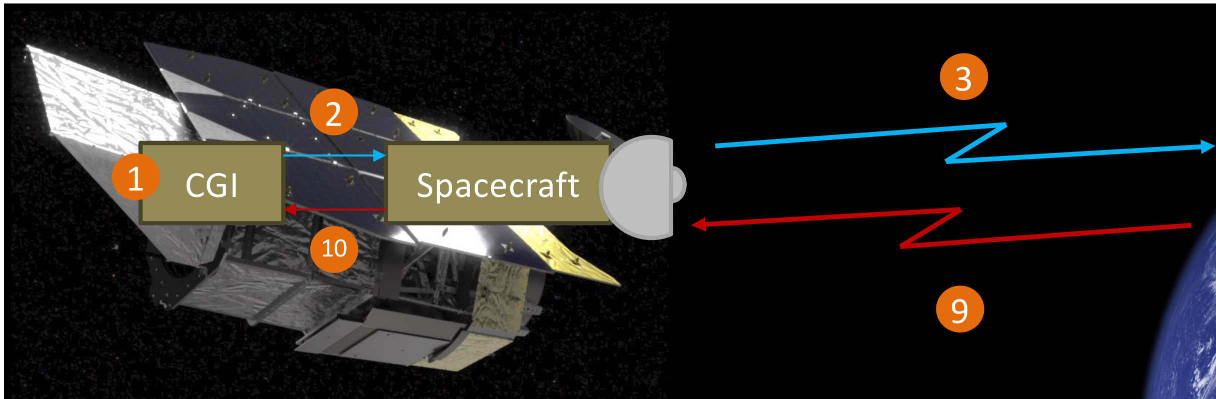
October 2019: Mission PDR raised red flags about FSW schedule risk, particularly for HOWFSC, along with mass/power

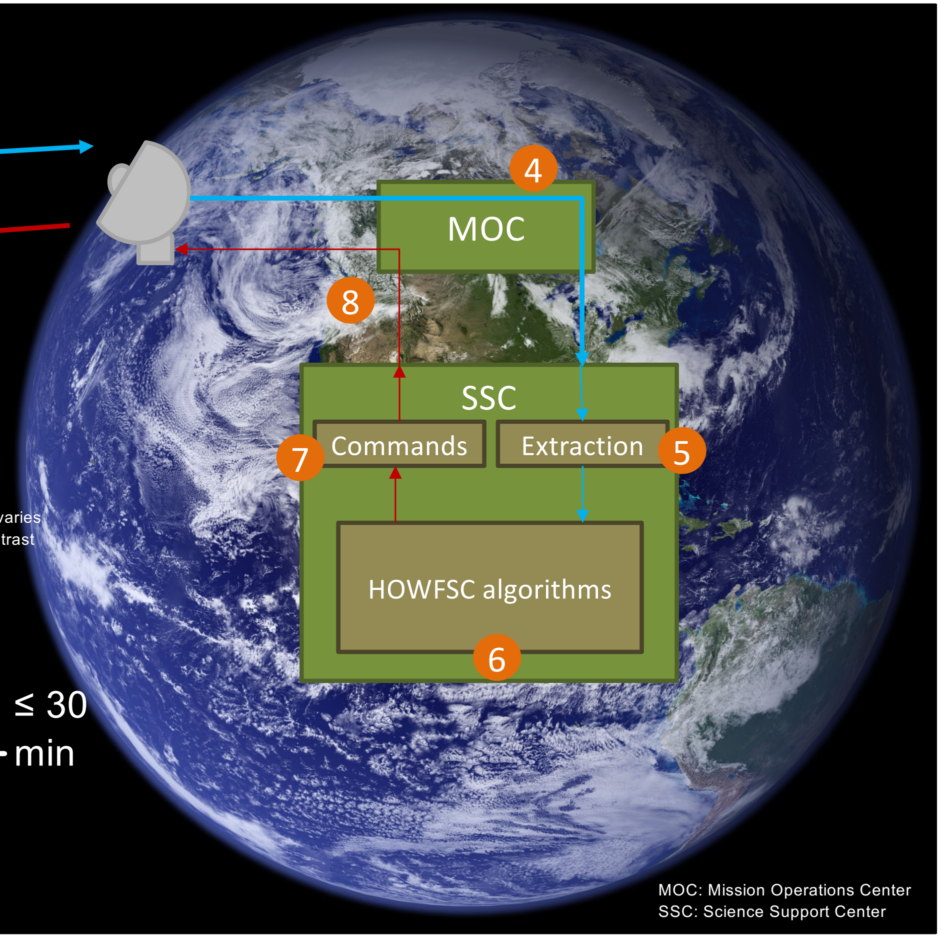
- Moved HOWFSC to GITL approach
  - On board: collect EXCAM data, process to "thin" Level 2b, combine and crop (for data volume)
  - On ground: run wavefront estimation and control on full set of images to select new DM setting
- Moved nearly all calibration, alignment, etc. functionality to ground as well, and descoped SSP and SSR

CGI benefits:

- Reduced mass/power/FSW lines of code/complexity and simplified V&V
  - A very real chance the CGI instrument would not have been able to be completed on time if this didn't occur
- Simpler and more effective implementation in GSW
  - Disjoint skillsets: FSW implementation required algorithm SMEs writing reference implementation with tests, and FSW engineers porting code and tests, to get around lack of personnel with HOWFSC *and* FSW experience
  - Timing/computation/storage issues disappear when modern COTS hardware can be thrown at the problem

Ground-in-the-loop (GITL) overview: flight





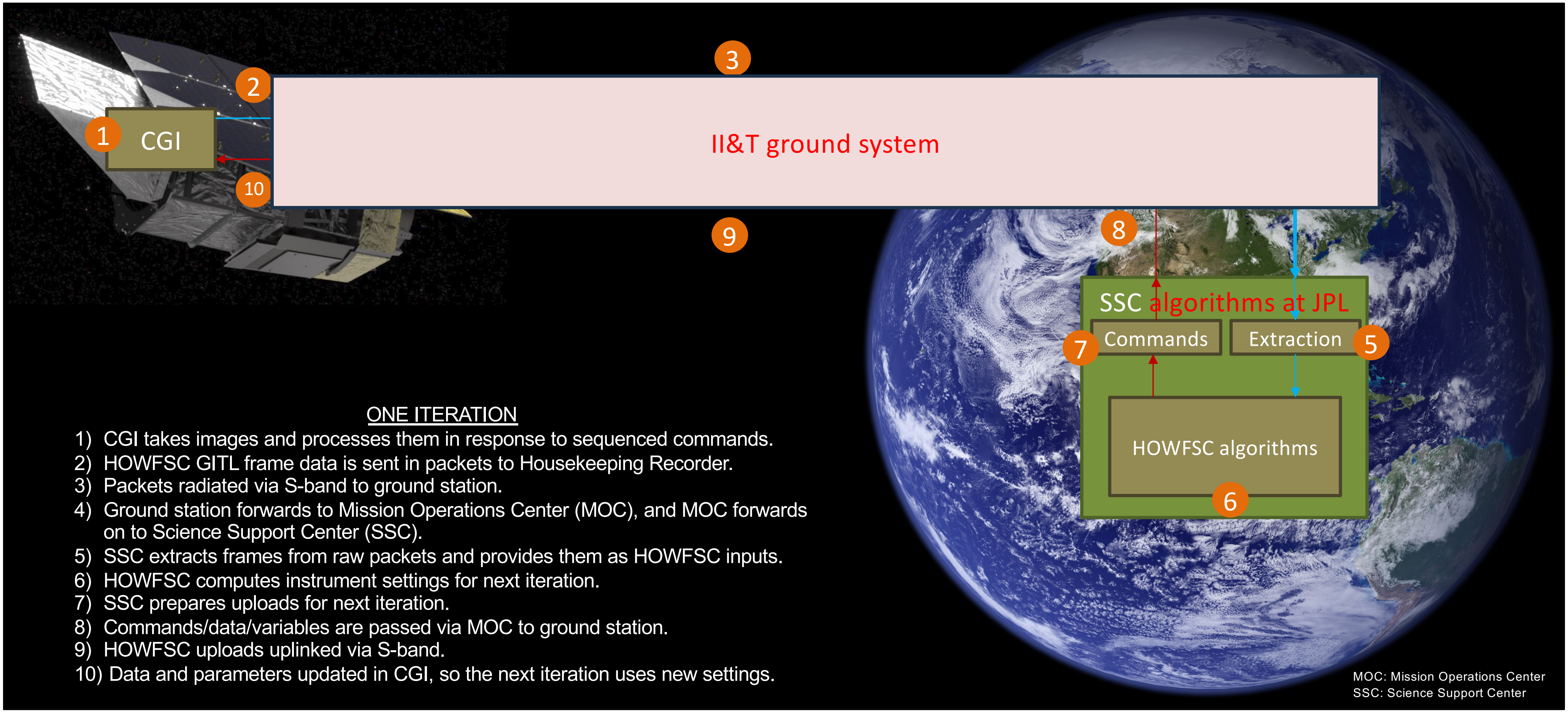
Length varies with contrast

<u>ONE ITERATION</u>

1) CGI takes images and processes them in response to sequenced commands.
2) HOWFSC GITL frame data is sent in packets to Housekeeping Recorder.
3) Packets radiated via S-band to ground station.
4) Ground station forwards to Mission Operations Center (MOC), and MOC forwards on to Science Support Center (SSC).
5) SSC extracts frames from raw packets and provides them as HOWFSC inputs.
6) HOWFSC computes instrument settings for next iteration.
7) SSC prepares uploads for next iteration.
8) Commands/data/variables are passed via MOC to ground station.
9) HOWFSC uploads uplinked via S-band.
10) Data and parameters updated in CGI, so the next iteration uses new settings.

(Steps 2–10: ≤ 30 min)

GITL overview: II&T TVAC



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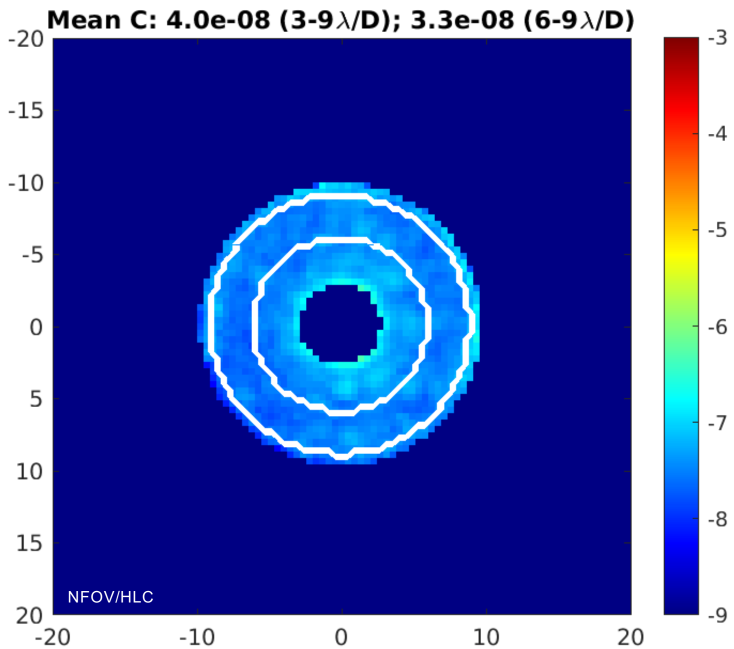
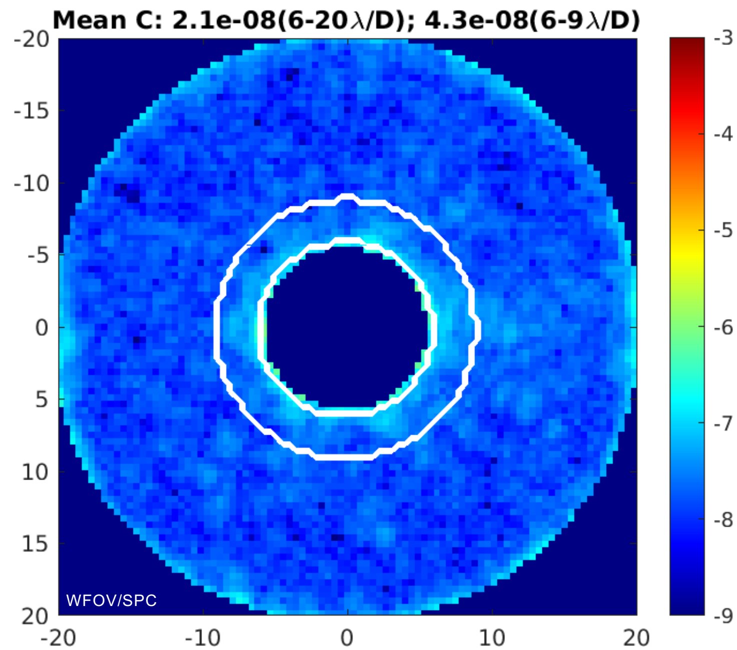
HOWFSC results summary

Performance summary





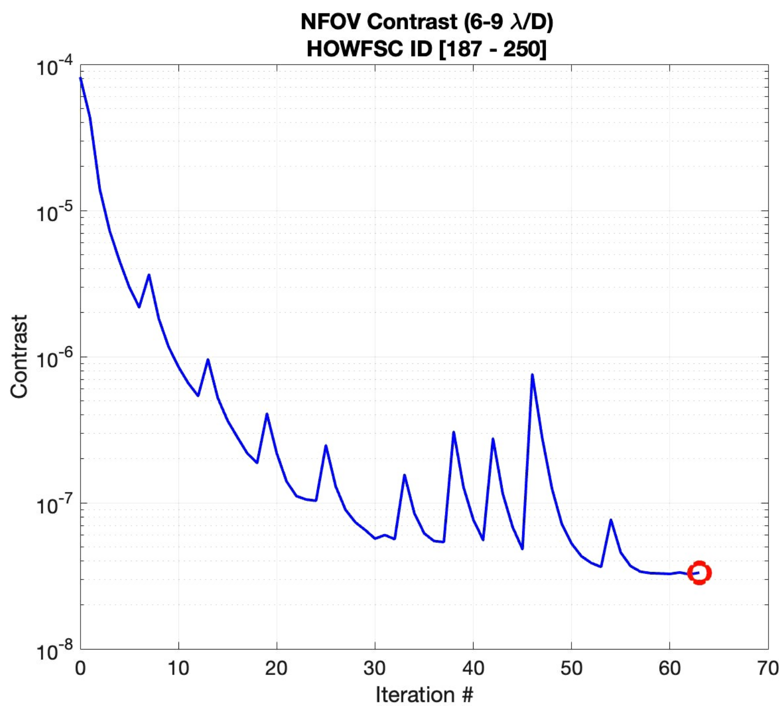
Results of >30 8-hour shifts of HOWFSC by the team:

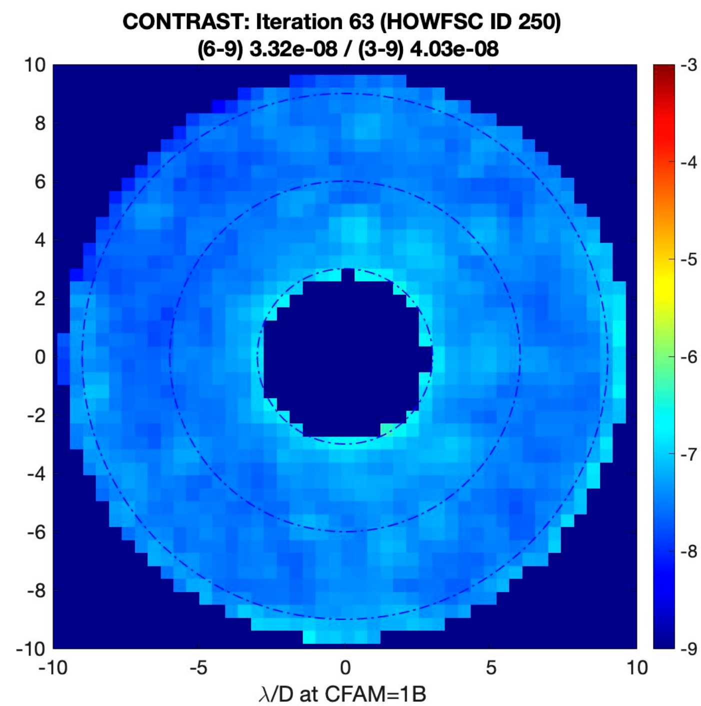
- Eric Cady,
- Byoung-Joon Seo,
- A.J. Riggs,
- Brian Kern,
- David Marx,
- Fang Shi,
- Hanying Zhou,
- John Krist,
- Garreth Ruane

Note: some ambiguity in coherent/incoherent split, so targeted total contrast ≤ 5e-8 (smaller of the two)

L4 Raw Contrast Requirements	Requirement	NFOV/HLC 6-9 λ/D Data	WFOV/SPC 6-9 λ/D Data
Imaging with Narrow FoV Initial Static Coherent Raw Contrast, 6-9 λ/D, narrow FoV mode, filter band 1	≤ 5×10^{-8}	0.98×10^{-8}	1.42×10^{-8}
Imaging with Narrow FoV Initial Static Incoherent Raw Contrast, 6-9 λ/D, narrow FoV mode, filter band 1	≤ 1×10^{-7}	2.35×10^{-8}	2.96×10^{-8}

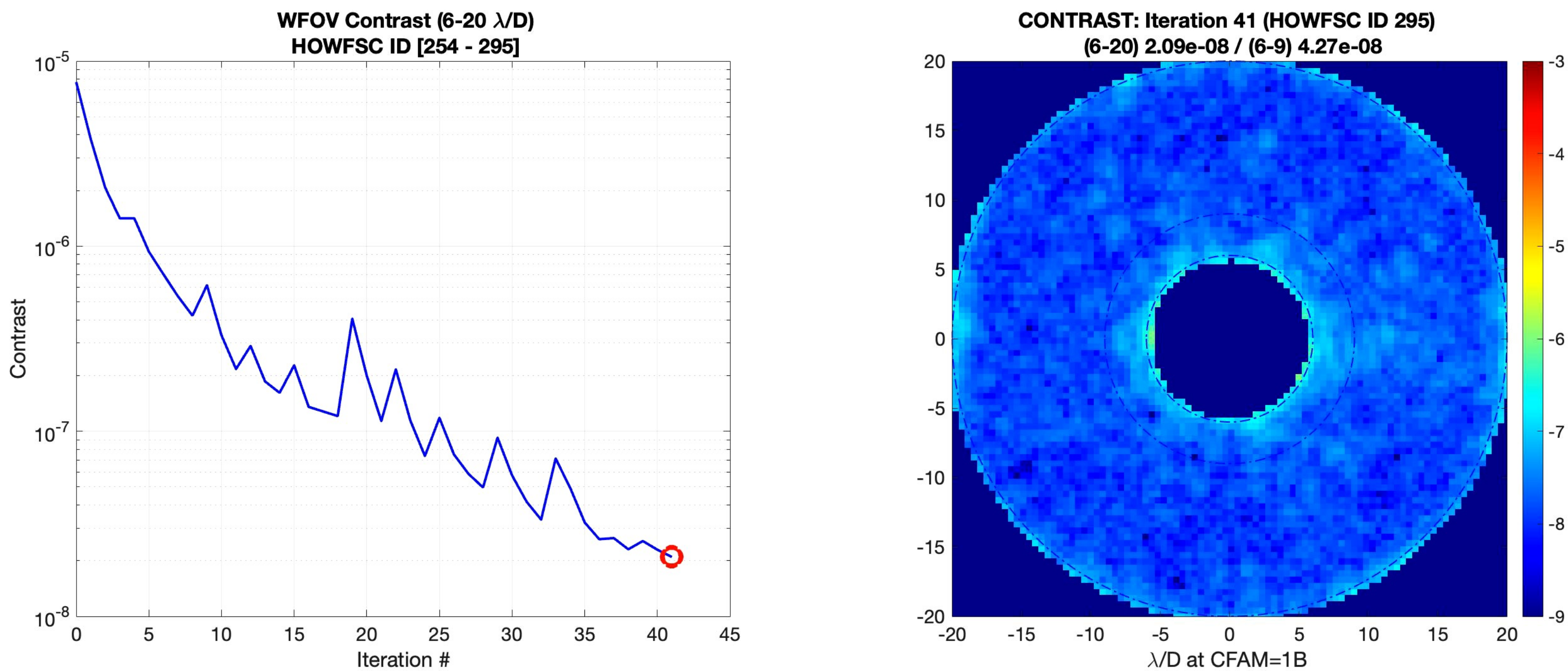
HOWFSC results: Band 1 narrow-field-of-view (NFOV)





- Control run over 3-9 λ/D; TTR5 region is 6-9 λ/D. (Third run shown)
- Coronagraph architecture: Hybrid Lyot Coronagraph
- Contrast limited by time available and incoherent light leak setting contrast floor (addressed by additional baffle post-TVAC)

HOWFSC results: Band 1 wide-field-of-view (WFOV)



- Control run over 6-20 λ/D; TTR5 region is 6-9 λ/D (One run only, shown above)
- Coronagraph architecture: Shaped Pupil Coronagraph
- Contrast limited by time available ("target of opportunity")

Open issues and lessons learned from TVAC

Stellar centration was a limiting factor on NFOV runs 1 and 2

- Model mismatch: control model centration not consistent with tilt from LOWFSC
- Root cause was incomplete tip-tilt removal in front-end phase retrieval (low points skewed fit)
- Iterations built up a decenter in the line-of-sight offsets
- Started from scratch for run 3 (shown in movie)
  - Updated software tools to keep phase retrieval from repointing PSF
  - Measured the centration with a dedicated data collection activity and included in the model, and added this activity to operations plan going forward

During nulling in runs 1-2, found that we needed to swap DM probes to probes centered at different places on the DM before

- Never seen this in technology maturation testing or model-based evaluations
- Root cause still under investigation (including if it was linked to the mismatch above)

Nice-to-have: increased confidence in the coherent/incoherent split, as incoherent requirements are looser

- Will require a delve into wavefront estimation theory

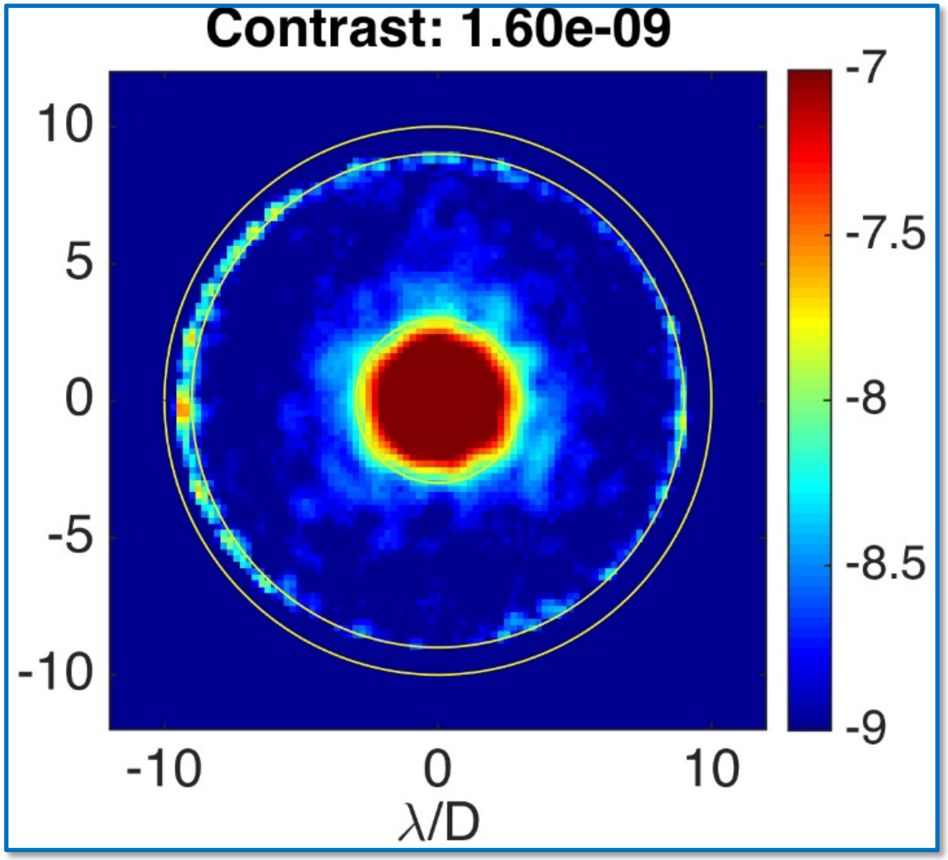
Summary

Key takeaways

- Achieved > TTR5-level performance with two independent coronagraph architectures covering 3-9 and 6-20 λ/D between them with a 360° dark hole on both
  - Ultimate CGI contrast floor not known—performance limited by available time rather than any identified instrument systematic
- HOWFSC and calibration GSW all worked together the first time in TVAC
  - Benefit of using high-heritage/high-TRL algorithms + extensive unit-level and functional testing in advance
- Tested in best test-as-you-fly configuration (onboard collection, CTC+SSC software on "ground" running HOWFSC)
  - End-to-end information transfer for GITL will be tested at the observatory level, with the entire ground system in the loop

BACKUP

Best tech maturation contrast: HLC in Milestone 9



Best HLC performance during Milestone 9 (2017) by Joon Seo

Roughly, this probably represents the achievably raw-contrast floor for HLC observations