High-Order Wavefront Sensing and Control

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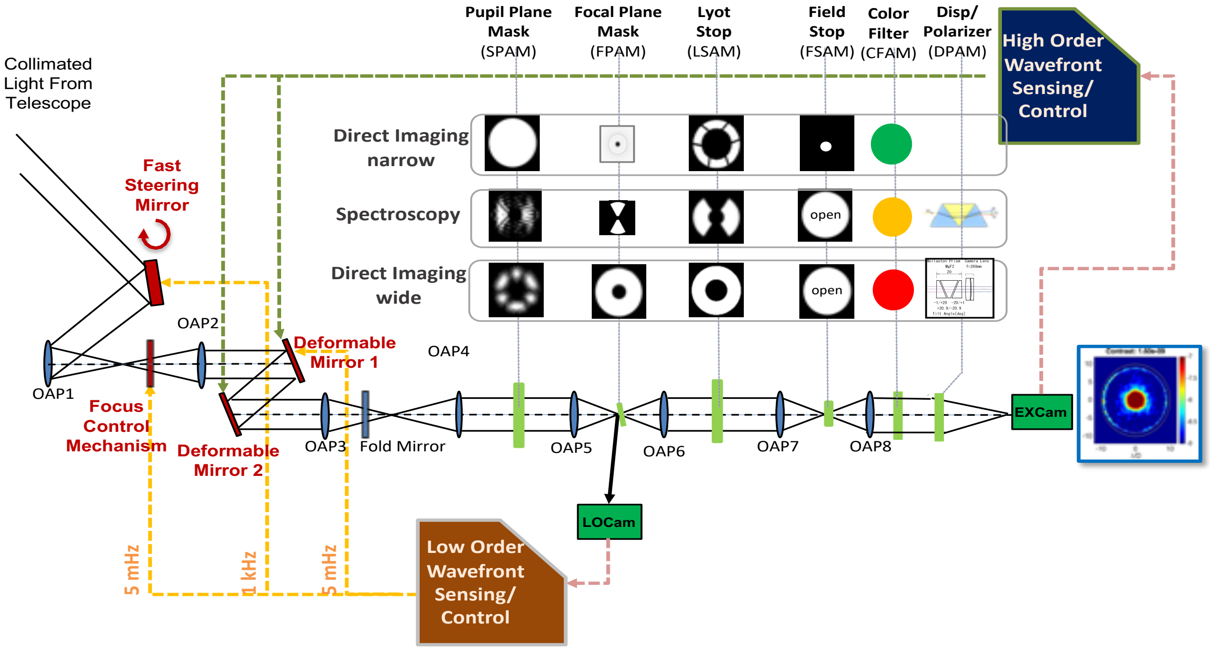
HOWFSC on the Roman Coronagraph

- High-Order Wavefront Sensing and Control – class of techniques to estimate and correct mid-spatial frequency wavefront errors.
- HOWFSC is one of the essential features enabling the Roman Coronagraph to surpass the starlight suppression performance of previous generations of coronagraph instruments.

HOWFSC Hardware Architecture

- The Roman Coronagraph actuates two **deformable mirrors** in series, and uses the **science camera (EXCam)** as a wavefront sensor.



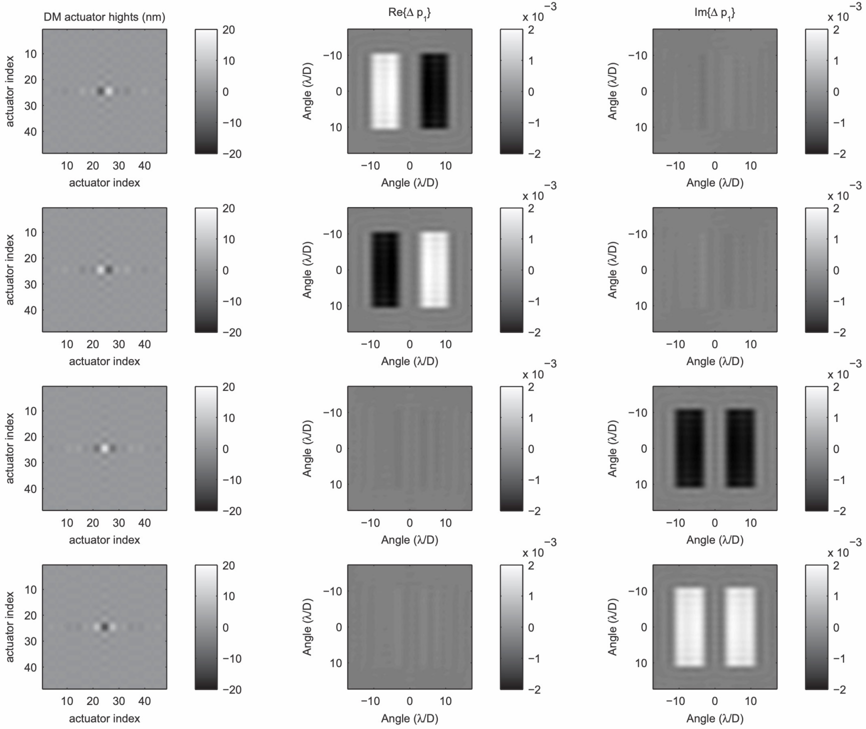
HOWFSC Algorithm (baseline)

- Electric Field Conjugation (EFC) with pairwise probes successfully applied in many JPL HCIT coronagraph demonstrations.
- EFC was used throughout all Roman Coronagraph Instrument demonstrations and milestones, including pre-Phase A work.
  E. Cady, K. Balasubramanian, et al., Proc. SPIE Vol 10400 (2017);
  http://dx.doi.org/10.1117/12.2272834
  B.-J. Seo, E. Cady, et al., Proc SPIE Vol 10400 (2017);
  http://dx.doi.org/10.1117/12.2274687

Baseline HOWFSC algorithm

- Apply a predefined series of probe patterns to the DM surface, modulating the aberrated intensity distribution in the focal plane.
- Image plane E-field estimated from differences of pair-wise (opposite phase) DM probe images.
- DM correction to cancel the estimated field determined by control matrix and regularization scheme.

DM probe shapes and corresponding focal plane fields



Give'on, Kern, Shaklan, Moody, Pueyo; Proc. SPIE (2007); https://doi.org/10.1117/12.733122

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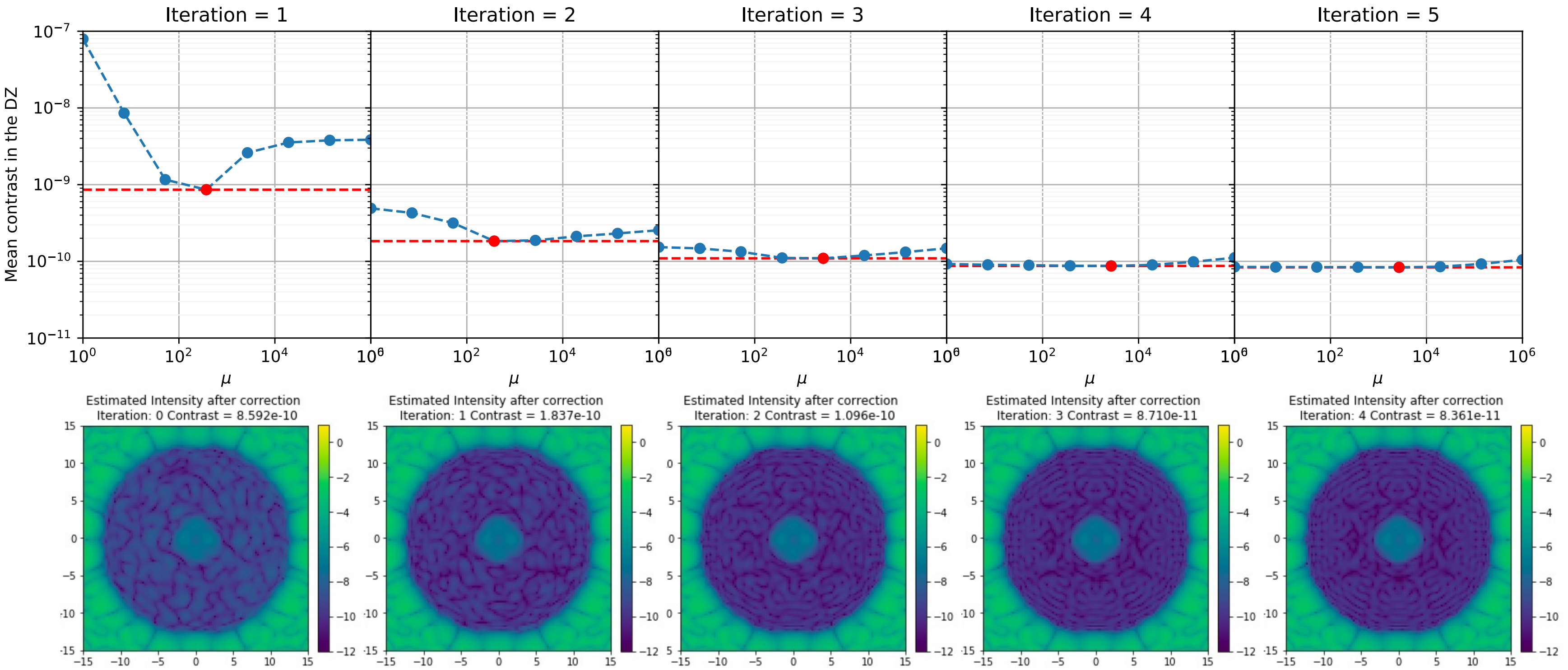
$$u_{w,k} = (G_k^* G_k + \alpha_k^2 \mathcal{I})^{-1} G_k^* \delta E_k.$$

- u – DM actuator command
- G – control matrix
- α – regularization parameter
- δE – desired change in image field

Groff, Riggs, Kern, Kasdin, "Methods and limitations of focal plane sensing, estimation, and control in high-contrast imaging" JATIS 2(1), 2016, https://doi.org/10.1117/1.JATIS.2.1.011009

EFC simulation (LUVOIR APLC example)

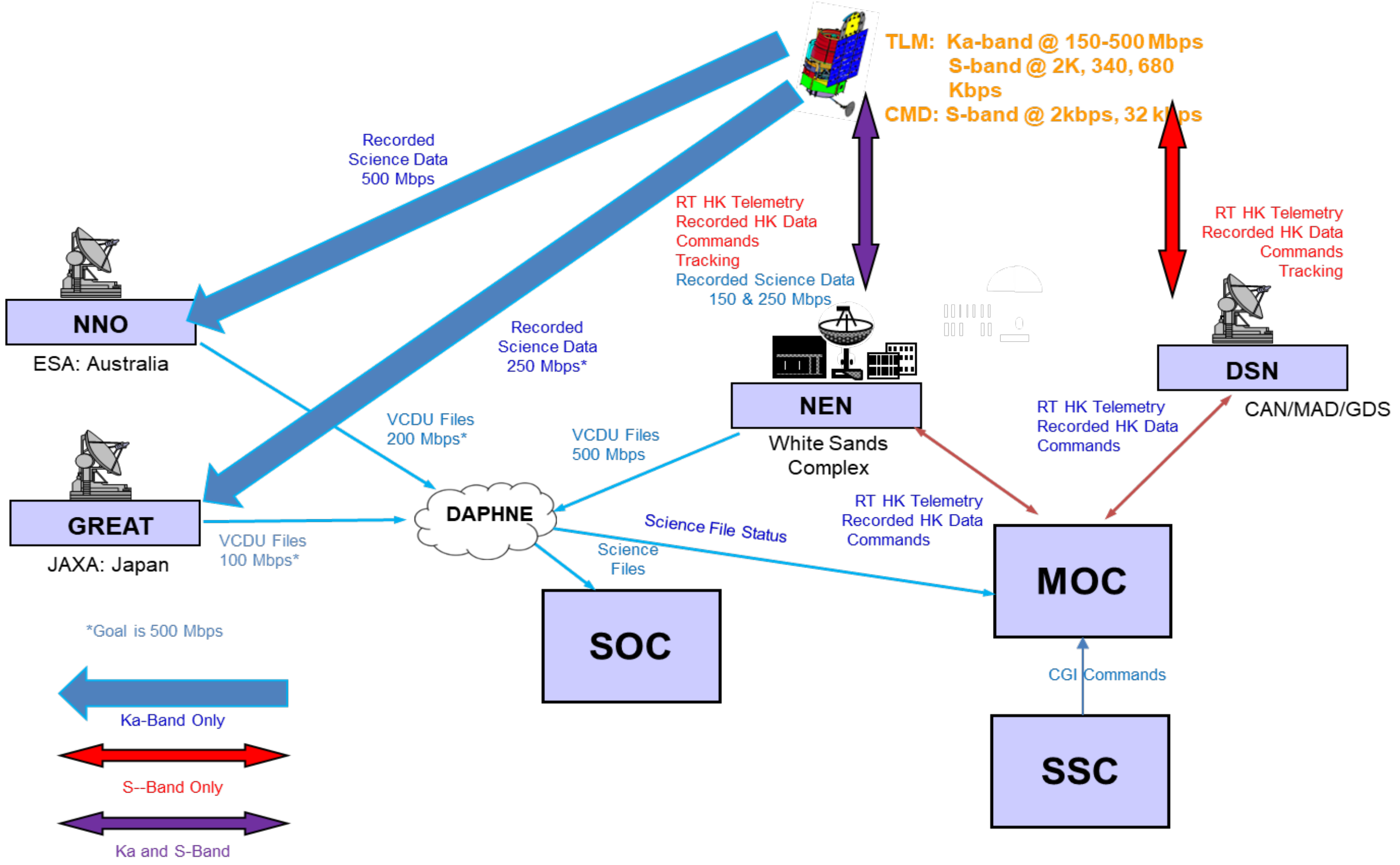


Simulations by Roser Juanola-Parramon:
Juanola-Parramon, Zimmerman, et al., IEEE Aerospace (2019); https://doi.org/10.1109/AERO.2019.8741658

Ground-in-the-Loop HOWFSC

- Up until Mission PDR, HOWFSC was slated to be performed by flight software
- In 2019 an external review team recommended switching to a ground-in-the-loop (GITL) HOWFSC scheme. This recommendation was evaluated and accepted by the Roman project.
  - Offload the computationally-expensive parts to the ground
  - Images are sent down via S-band (stacked, cleaned and cropped)
  - Deformable mirror (DM) settings and camera settings for the next control iteration are sent back up
  - No required operator in the loop

Ground-in-the-Loop HOWFSC



Ground-in-the-Loop HOWFSC

M×N cleaned cropped images, taken with filter/DM combinations
- M = number of engineering subfilters (3 or 5)
- N = number of DM1 settings (~7)
- Cropped to ~153×153 from 1024×1024 (≤44λ/D per side)

M×N Boolean bad pixel maps
- same size as images

Every iteration (~7-9 per obs)

HOWFSC/GITL software

Every iteration (~7-9 per obs)

N+1 DM settings
- N = number of DM1 settings (~7)
- Each a 48×48 array
- One additional common DM2 setting

N camera settings
- 3 values each: gain, exposure time, number of frames

N low-order-control offsets
- 10 values derived from DMs each

HOWFSC as part of the tech demo

One of the five Technology Demonstration Objectives:

The CGI will support development and in-flight demonstration of coronagraph software that could enhance the capability or simplify the architecture of future missions. WFIRST would fulfill this objective by demonstrating the ability to modify the wavefront sensing and control algorithms during the prime science mission.

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- Any HOWFSC modifications would require substantial involvement from the CTC and the SSC staff.

Dark Hole Algorithms Working Group

- Encourage research on algorithms that could enhance the value of the Roman Coronagraph tech demo.
- Information conduit from Coronagraph Project team on instrument design, operations constraints, and simulation inputs.
- A forum to present and comment on concepts and lab demos for alternative HOWFS algorithms.

Dark Hole Algorithms Working Group

Roman Project / CGI
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Eric Cady (JPL)
Tyler Groff (GSFC)
Brian Kern (JPL)
John Krist (JPL)
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Wolfgang Brandner (MPIA)
Vincent Deo (NAOJ)
Markus Feldt (MPIA)
Johan Mazoyer (Obs. Paris)
Frans Snik (Leiden)

Dark Hole Algorithms Working Group

- 11/13/20 – Simulations: DH maintenance (Leonid Pogorelyuk), FALCO and CGISIM (A.J. Riggs)
- 1/28/21 – Multi-star wavefront control (Dan Sirbu), Demonstrations of DH maintenance on HiCAT (Susan Redmond)
- 3/10/21 – HOWFSC on SCExAO (Olivier Guyon), System ID on Ames testbed (Vincent Deo)
- 6/30/21 – HOWFSC on THD / Obs. Paris (Raphaël Galicher, Pierre Baudoz)

HOWFSC Simulation Tools

	Contact	URL	Reference
FALCO	A.J. Riggs (JPL)	https://github.com/ajeldorado/falco-matlab	Riggs et al., SPIE Proc. 10698 (2018): https://doi.org/10.1117/12.2313812
CGISim	John Krist (JPL)	https://sourceforge.net/projects/cgisim/	Krist et al., JATIS Volume 2, id. 011003 (2016): https://doi.org/10.1117/1.JATIS.2.1.011003
Lightweight Space Coronagraph Simulator	Leonid Pogorelyuk (MIT)	https://github.com/leonidprinceton/LightweightSpaceCoronagraphSimulator	Pogorelyuk et al., SPIE Proc. 11823 (2021): https://doi.org/10.1117/12.2594679

BACKUP

ROMAN SPACE TELESCOPE

Wavefront Control

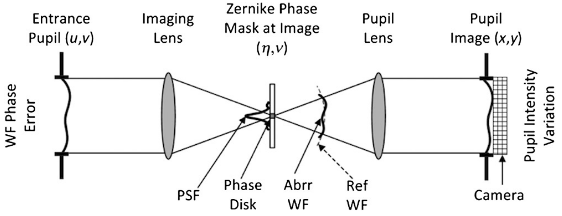
Jet Propulsion Laboratory
California Institute of Technology

- The baseline CGI design includes four active optics to control the wavefront: a **fast steering mirror** (FSM), a flat **focusing mirror** (FCM), and two **deformable mirrors** (DM 1 and DM 2) with 48x48 actuators each.

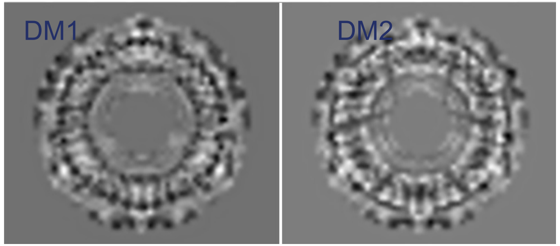
- High-order wavefront control is implemented by the Electric Field Conjugation (EFC) method. The EFC loop operates on science focal plane data by measuring the interaction of aberrated on-axis starlight with a sequence of DM actuator probes.

- Pointing, focus, and low-order wavefront drifts are sensed by the **Low-Order Wavefront Sensing and Control** (LOWFS/C) subsystem using the Zernike phase-contrast technique on starlight rejected from the occulting mask. Corrections to Zernike modes Z5—Z11 are applied to DM 1.

- The FSM control loop corrects line-of-sight pointing jitter to below 0.95 milliarcsec.



Conceptual diagram of the Zernike phase contrast wavefront sensor (F. Shi, et al., 2016).



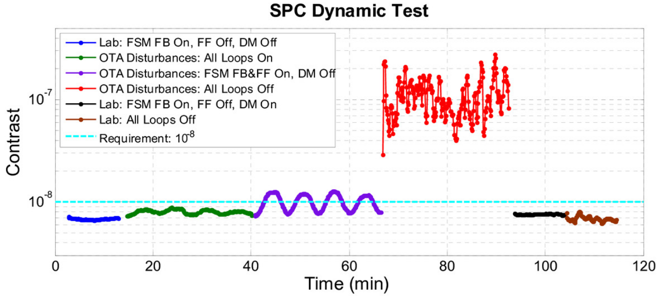
Optimized DM surfaces applied in HLC data simulations.

References

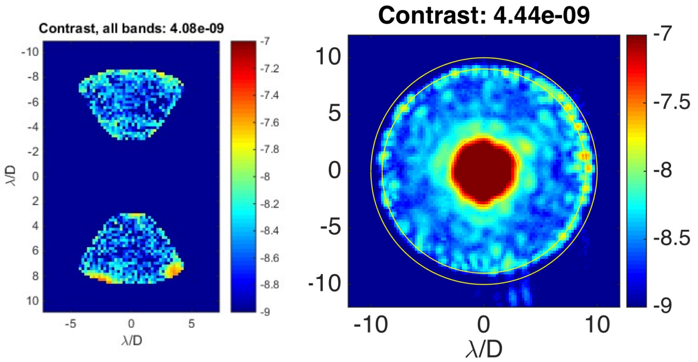
- T. Groff, A. J. E. Riggs, et al., JATIS Vol 2, id 011009 (2015) - https://doi.org/10.1117/1.JATIS.2.1.011009
- F. Shi, et al., JATIS Vol 2, id 011021 (2016) - https://doi.org/10.1117/1.JATIS.2.1.011021
- J. Krist, et al., JATIS Vol 2, id 011003 (2015) - https://doi.org/10.1117/1.JATIS.2.1.011003

Laboratory Demonstrations

Results from the Occulting Mask Coronagraph (OMC) Testbed at JPL HCIT



Dynamic contrast demonstration with a Low Order Wavefront Sensing and Control (LOWFS/C) system integrated on the Occulting Mask Coronagraph testbed. When line-of-sight disturbances and low order wavefront drift (slow varying focus) are introduced on the testbed, the LOWFS senses the pointing error and wavefront drift and corrects them by commanding a fast steering mirror and one of the DMs. Demonstrations with both the SPC and HLC masks surpassed their 1E-8 contrast goal (F. Shi, et al., Proc SPIE Vol 10400, 2017).



Normalized intensity maps measured on the OMC testbed in broadband (10 %) light for SPC (left) and HLC. The total contrast between 3 – 9 λ/D is listed on top of each figure.

References

- F. Shi, E. Cady, et al., Proc. SPIE Vol 10400 (2017) - http://dx.doi.org/10.1117/12.2274887
- E. Cady, K. Balasubramanian, et al., Proc. SPIE Vol 10400 (2017) - http://dx.doi.org/10.1117/12.2272834
- B.-J. Seo, E. Cady, et al., Proc SPIE Vol 10400, 10.1117/12.2274687 (2017) - http://dx.doi.org/10.1117/12.2274687
- F. Shi, et al., Proc. SPIE Vol 10698 (2018) - https://doi.org/10.1117/12.2312746
- B.-J. Seo, et al, Proc. SPIE Vol 10698 (2018) - https://doi.org/10.1117/12.2314358
- D. Marx, et al, Proc. SPIE Vol 10698 (2018) - https://doi.org/10.1117/12.2312602
- F. Shi, et al., Proc. SPIE Vol 11117 (2019) - https://doi.org/10.1117/12.2530486