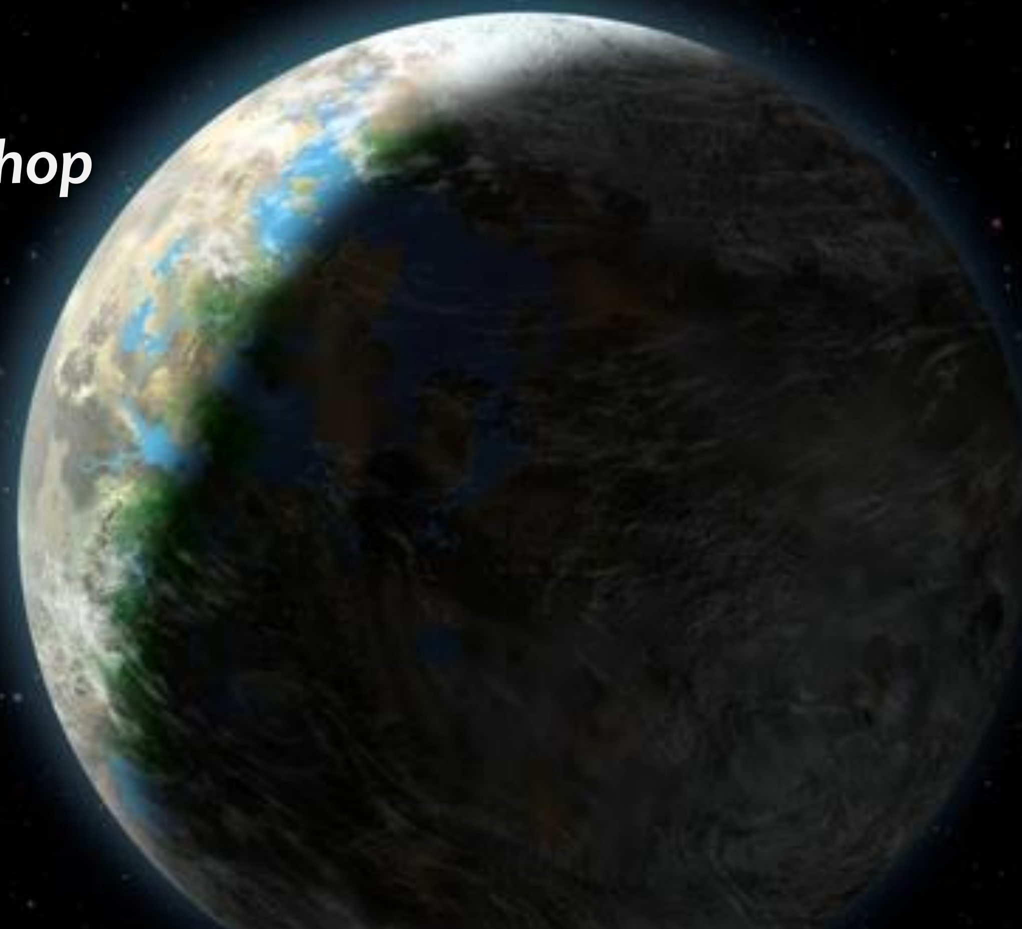
WFIRST Coronagraph Instrument technology advancement update



Mirror Technology Workshop

SPIE

2016–11-03

Richard T. Demers

Jet Propulsion Laboratory

WFIRST CGI Team

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1 Jet Propulsion Laboratory, California Institute of Technology

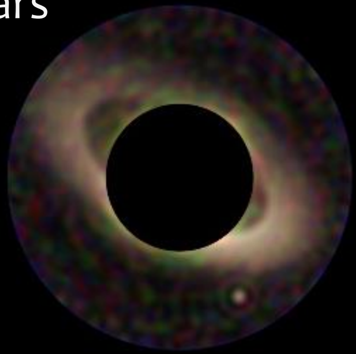
2 NASA Goddard Space Flight Center

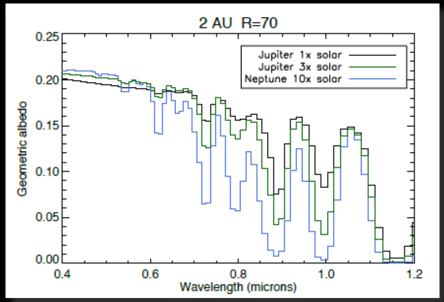
WFIRST = Wide Field InfraRed Survey Telescope

- 2.4 Meter Telescope
- Wide Field Instrument
- Coronagraph Instrument (tech demo)

Coronagraph Science

- Direct Exoplanet imaging
- Atmospheric compositions of planets
- Characterize debris disks around nearby stars





CGI Objectives – Phase A

- CGI System requirements flow
  - Science & Engineering key and driving requirements
  - Interface control documents
  - Critical design trades
- Complete Technology Milestones
  - Closely followed by NASA HQ
- Gate products
  1. System Requirements Review (SRR)
  2. Mission Definition Review (MDR)

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Starlight Suppression Technology

- Coronagraph pupil, focal plane & Lyot stop masks
- Wavefront sensing & control
  - High order WFC for dark field
  - Low order WFC for speckle stability
- Pointing control & contrast stability
- Deformable mirror
- Low noise detector for imaging & spectrograph cameras
- Post processing algorithms for speckle removal

SPIE Edinburgh 2016

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Technology Milestones

MS #	Milestone	Date
1 ✓	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 µm pixel size.	7/21/14
2 ✓	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14
3 ✓	First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of 10^{-8} raw contrast with 10% broadband light centered at 550 nm.	12/15/14
4 ✓	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	2/28/15
5 ✓	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment.	9/15/15
6 ✓	Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.	9/30/15
7 ✓	Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.	8/25/16
8	PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.	9/30/16
9	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.	9/30/16

✓ Reviewed and approved by Technical Assessment Committee

Draft reports submitted, review with Technical Assessment Committee scheduled Nov 8

Static Testbed Recap (Milestone 5)

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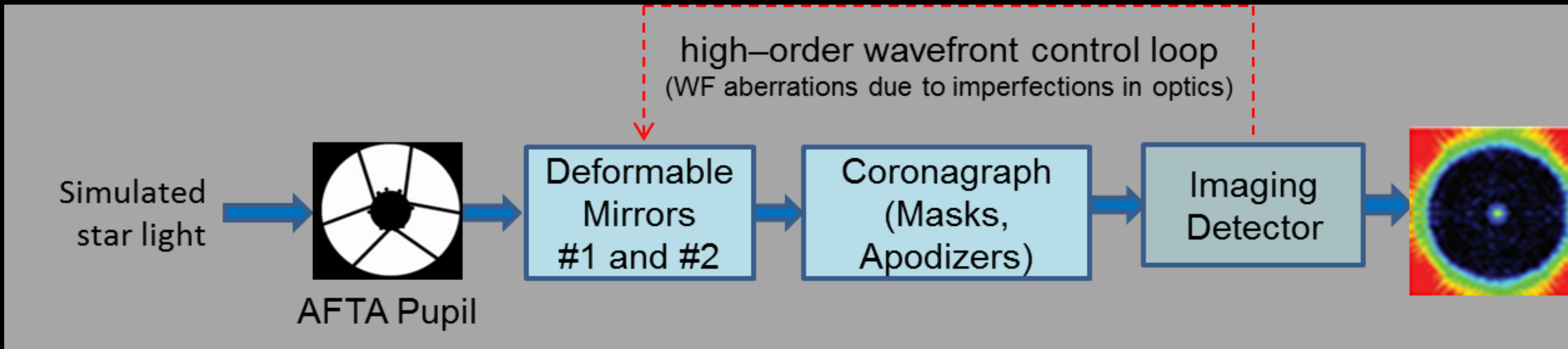
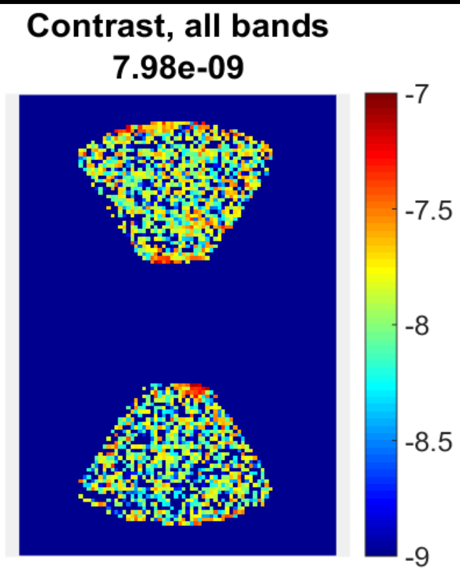
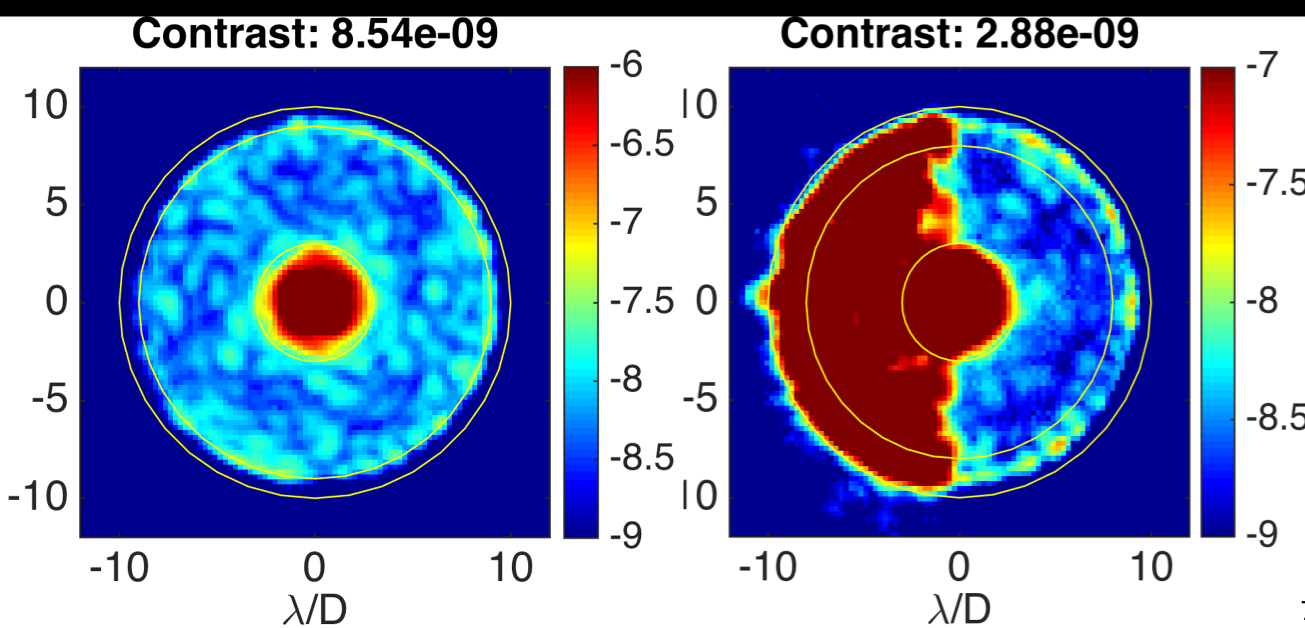
Both shaped pupil and hybrid Lyot coronagraph designs for WFIRST attained ~8×10^{-9} raw contrast in their respective static testbeds



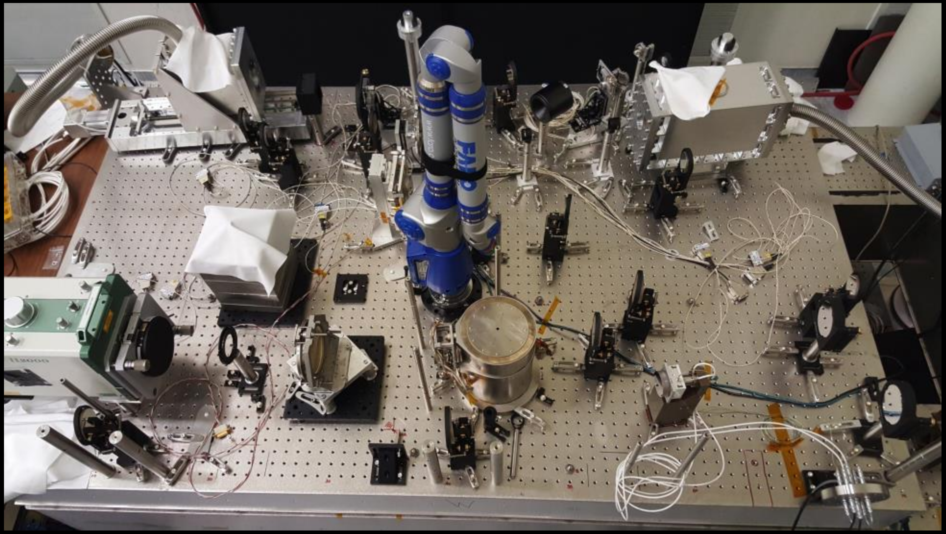
SPC, 10% band

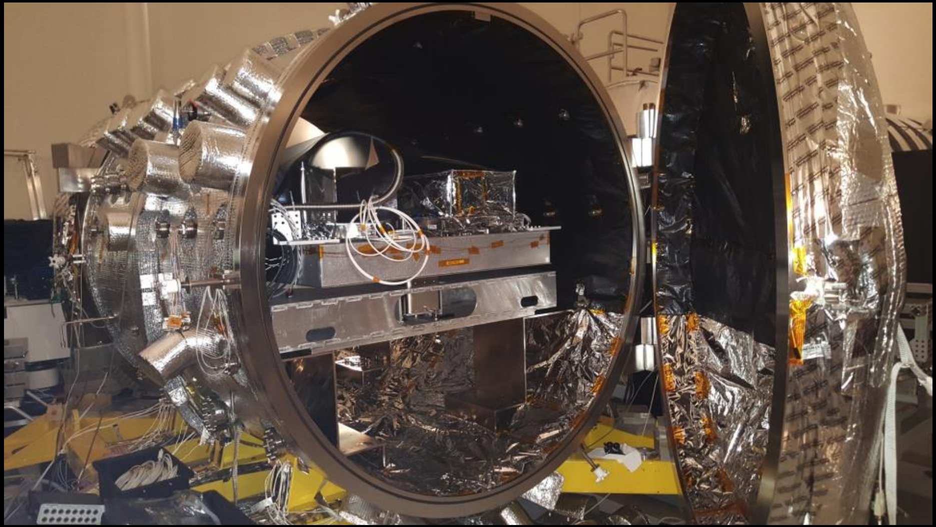


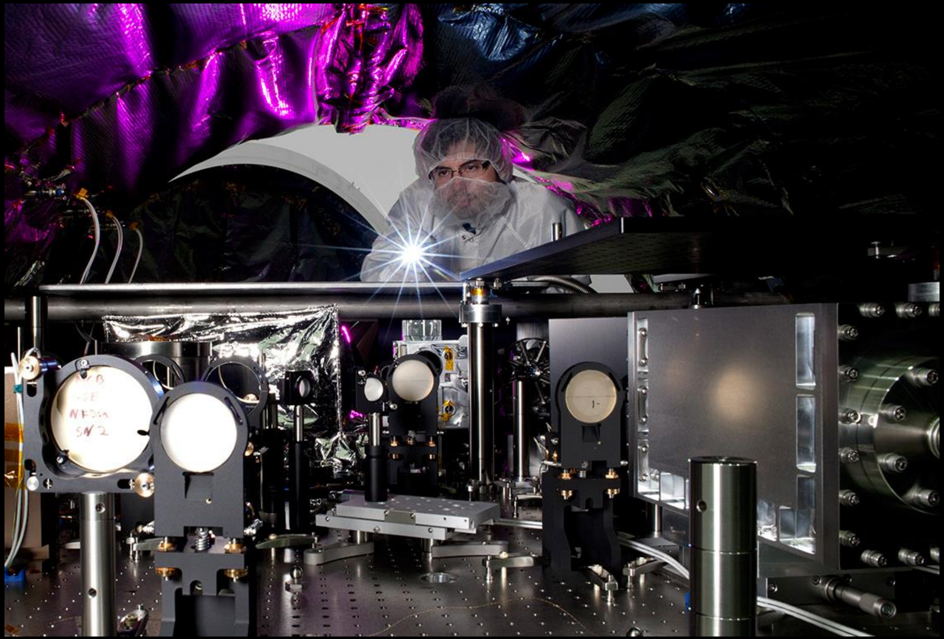
HLC, 10% band



New OMC Dynamic Testbed







Milestone 9 Report

Aspect of Milestone 9	Status	Comments
Coronagraph works with tip/tilt loop closed	Done	Pointing error suppression demonstrated in HLC mode.
Coronagraph works with LOWFE loop closed using DM	Done	Low order wavefront control demonstrated with deformable mirror
Broadband 10% dark hole $< 10^{-8}$	Broadband HLC <u>modulated</u> light $<10^{-8}$ <u>Unmodulated</u> light $\sim 2 \times 10^{-8}$ attributed to GSE	Current results (2.8×10^{-8}) are dominated by unmodulated light generated by OGSE (pseudo star + telescope simulator). We know from Milestone 5 that both HLC and SPC designs under test can create broadband 10% dark hole $< 10^{-8}$ with WFIRST pupil.
Measure throughput	Done	Measured geometric and Strehl throughput
Simulate planet	Done	Optically introduced simulated off-axis planet
Model validation and testbed error budgets	Done	Good correlation (MUF < 2) of model prediction and CGI testbed performance (GSE effects aside).

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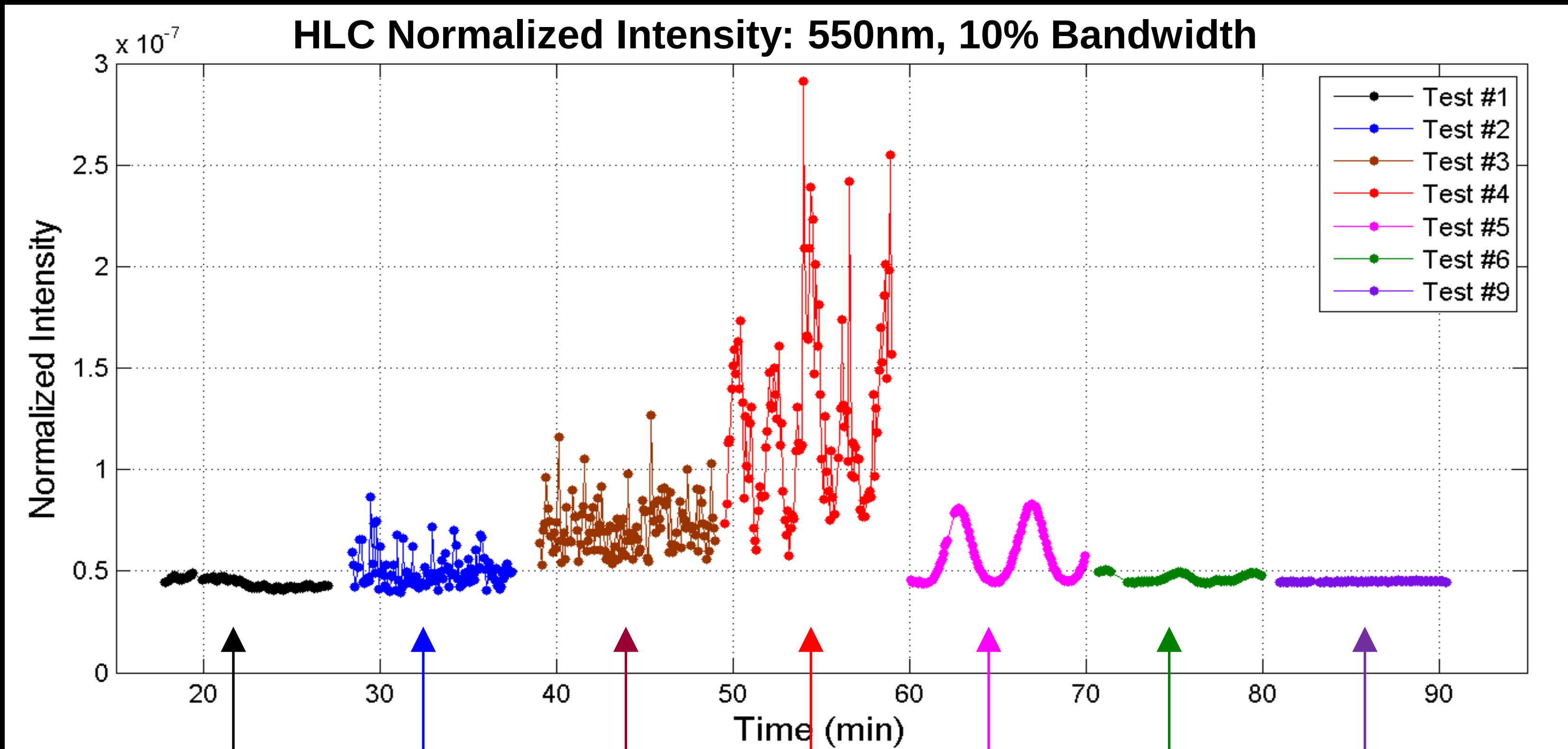
HLC + OTA-S + LOWFS/C Dynamic Test



Open Loops: Lab Environment

Open Loops: LoS ACS Drift

Open Loops: LoS ACS Drift + RWA Jitter (600rpm)

Open Loops: LoS ACS Drift + RWA Jitter + Focus Sine Wave Disturbance

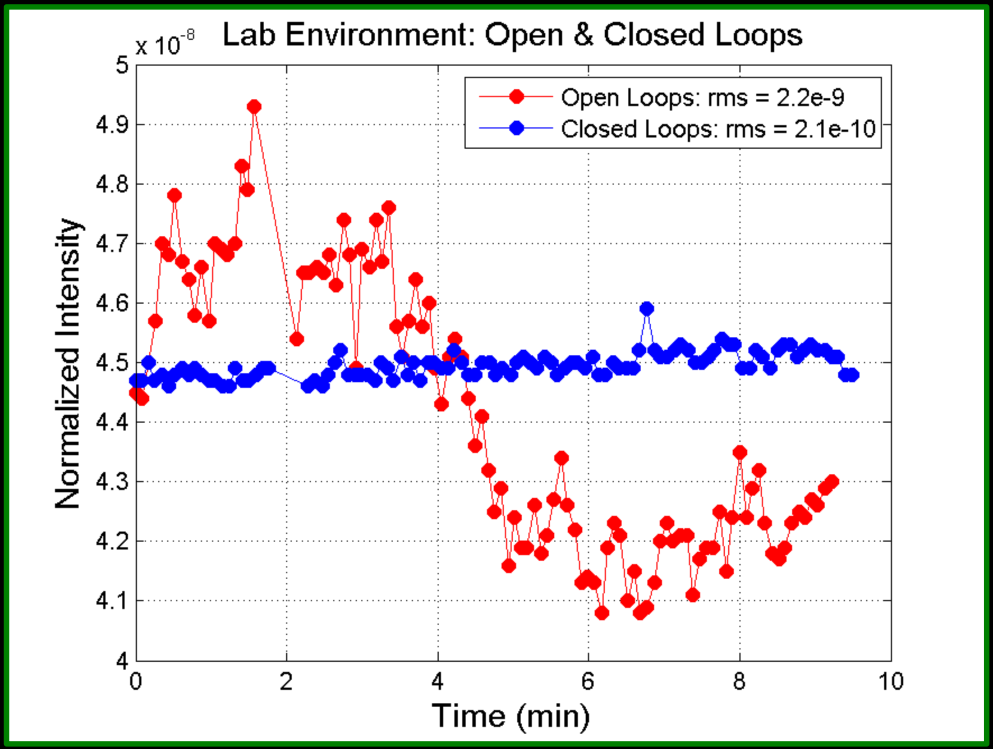
Close FSM FB&FF Loops: LoS ACS Drift + RWA Jitter + Focus Sine Wave

Close FSM & DM Loops: LoS ACS Drift + RWA Jitter + Focus Sine Wave

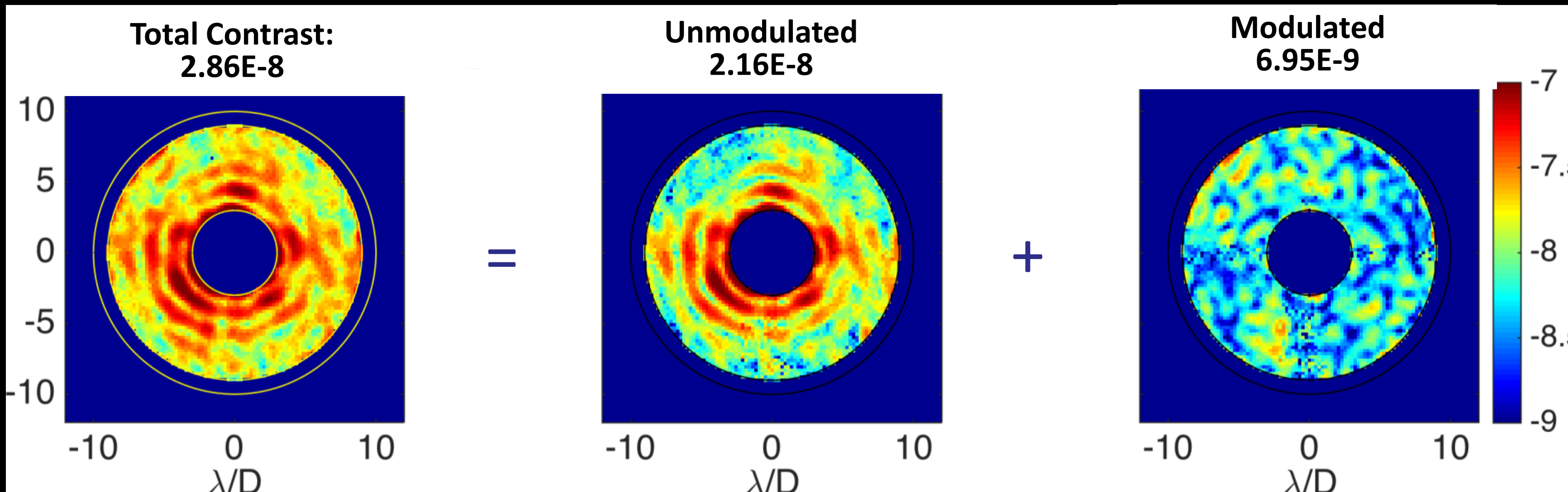
Close FSM-FB & DM Loops: Lab Environment

Contrast Stability Improved by LOWFS/C: Lab Environment

- **HLC contrast stability under the lab environment improved with LOWFS/C on**
  - The plot nearby compares HLC dark hole stability for open- and closed loops
  - The rate of lab LOWFE drift is comparable to the WFIRST flight conditions
  - **RMS stability improved from 2.2×10^{-9} to 2.1×10^{-10}**



OMC/HLC Contrast Summary

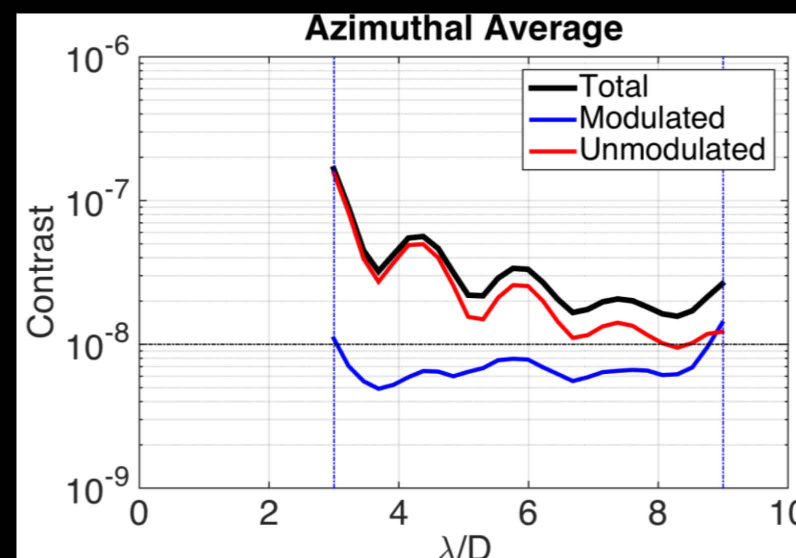


Performance:

- **Averaged raw contrast: 2.86×10^{-8}**
- Accuracy: ±10%

Configuration:

- 3 - 9 λ/D 360° dark hole
- 10% bandwidth centered at 550 nm
- Mask fabricated by e-beam lithography
- 3 um pinhole "star" illuminated by fiber tip
- Dominated by unmodulated light from GSE



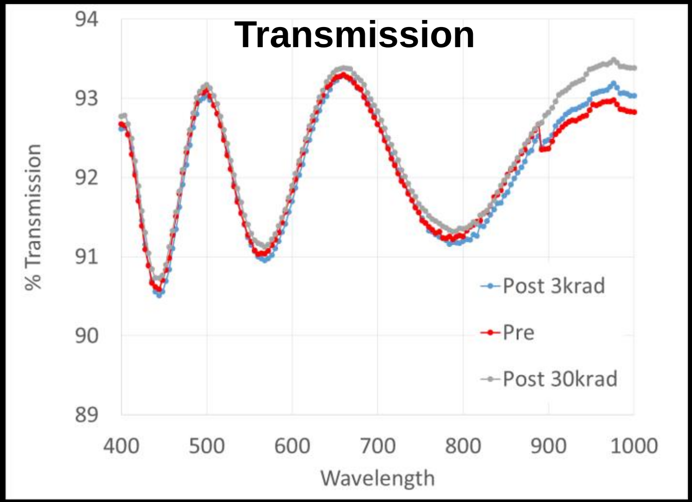
Test-Bed Model Validation

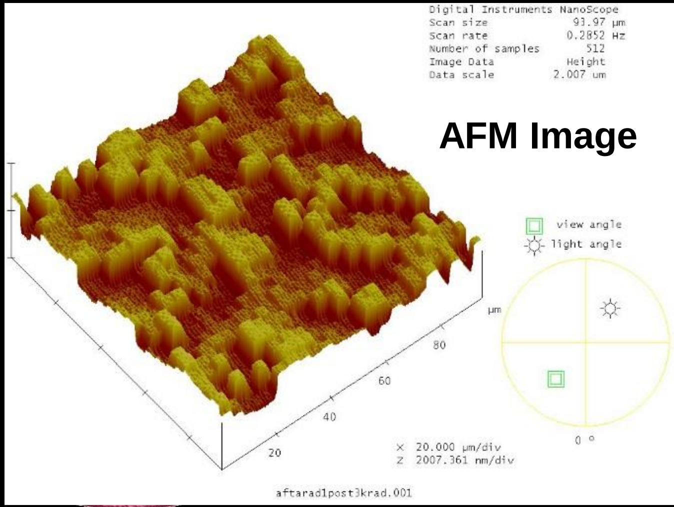
- Significant recent progress on test-bed error budgets & model validation
- Current simulations generate "coherent" residual starlight predictions within MUF=2 of test-bed results
- Most discrepancies from design are measured & captured in CGI control model
- CGI performance dominated by measurement or knowledge errors

	Probing	DM stroke limit	Regularization limit	Calibration Error	Predicted Mean Contrast
Case 0*	No	No	No	No	**2.00E-10**
Case 2*	Yes	Yes	No	No	6.00E-10
Case 3*	Yes	No	Yes	No	3.00E-09
Case 4'	Yes	Yes	Yes	No	3.88E-09
Case 4	Yes	Yes	Yes	No	6.63E-09
Case 5	Yes	Yes	Yes	Yes (MC only)	8.63E-09

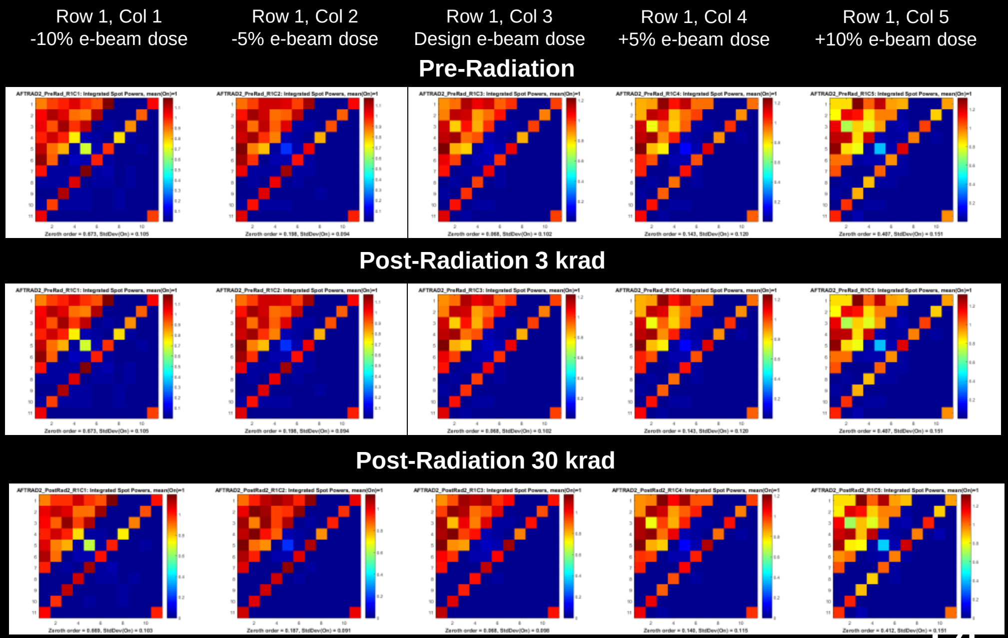
HLC Mask TRL Advancement

- PMGI as a patternable dielectric material to fabricate HLC occulting masks
- Previously, the rad hardness of the PMGI was not known in transmission.
- **JPL** - Four techniques (AFM, UV-Vis Transmission, Ellipsometry, and Computer Generated Holograms) used to characterize the impact of Co-60 radiation. No effect observed up to 200X mission TID (300 krad, 6 years at L2, RDF=2)
- **UC Davis** - Proton radiation testing for similar dosages showed no change in CGH testing, and only slight darkening (~4% decrease in transmission)





Computer Generated Hologram



Integration of IFS to HCIT

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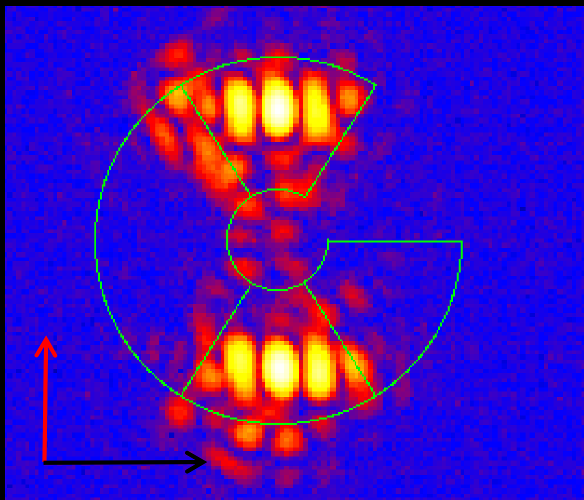
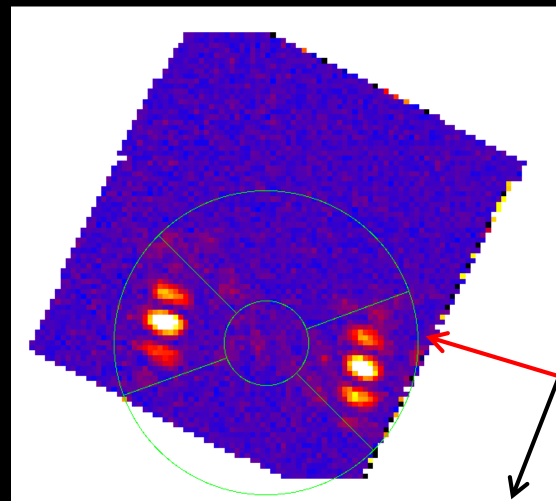
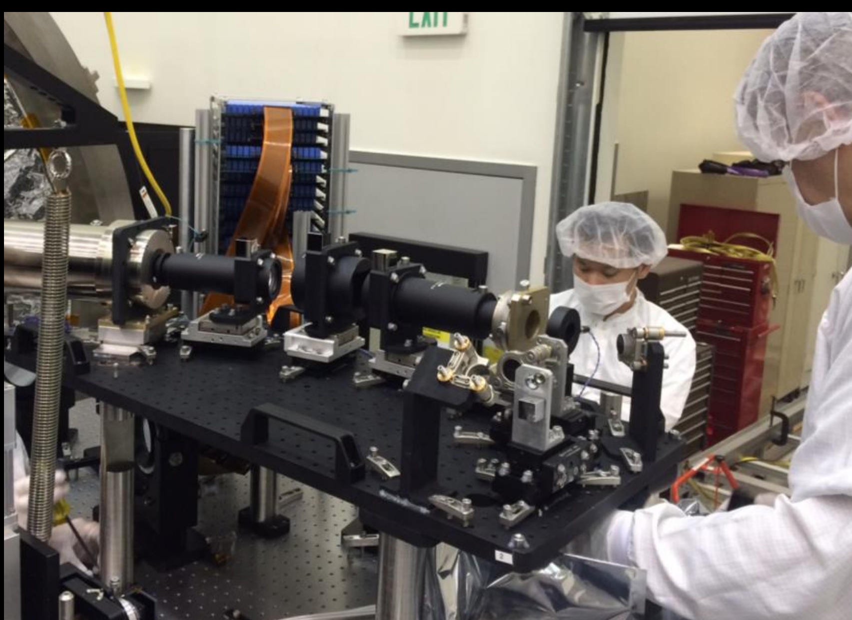
Image Cam Dark Hole



IFS image after extraction



- Floor contrast: 5e-8
- Measured 3.3 lenslets per λ/D
- Spectral calibration completed
- Dark hole observed on IFS
- Next step: produce broadband dark hole using & two DM's & IFS for WFSC



IFS Specifications			
Band center wavelength (nm)	660	780	920.0
λmin (nm)	600	706	833
λmax (nm)	719	850	1000
# of dispersed pixels	25.2	25.2	25.2
Instantaneous bandpass	18%	18%	18%
f/#	870	870	870
Lenslet pitch (μm)	174	174	174
Lenslet sampling at λ_c [# lenslets/(λ_c/D)]	3.3	3.9	4.6
FOV (# of λ_c/D*) [radius]	11.6	9.8	8.3
FOV (arcsec) [radius]	0.65	0.65	0.65
Pinhole diameter [microns]	25 - 30		
Lenslet array format	76×76		
Magnification from lenslet to detector	1:1		
Spectral resolution [over 2 pixels]	70 ± 5		

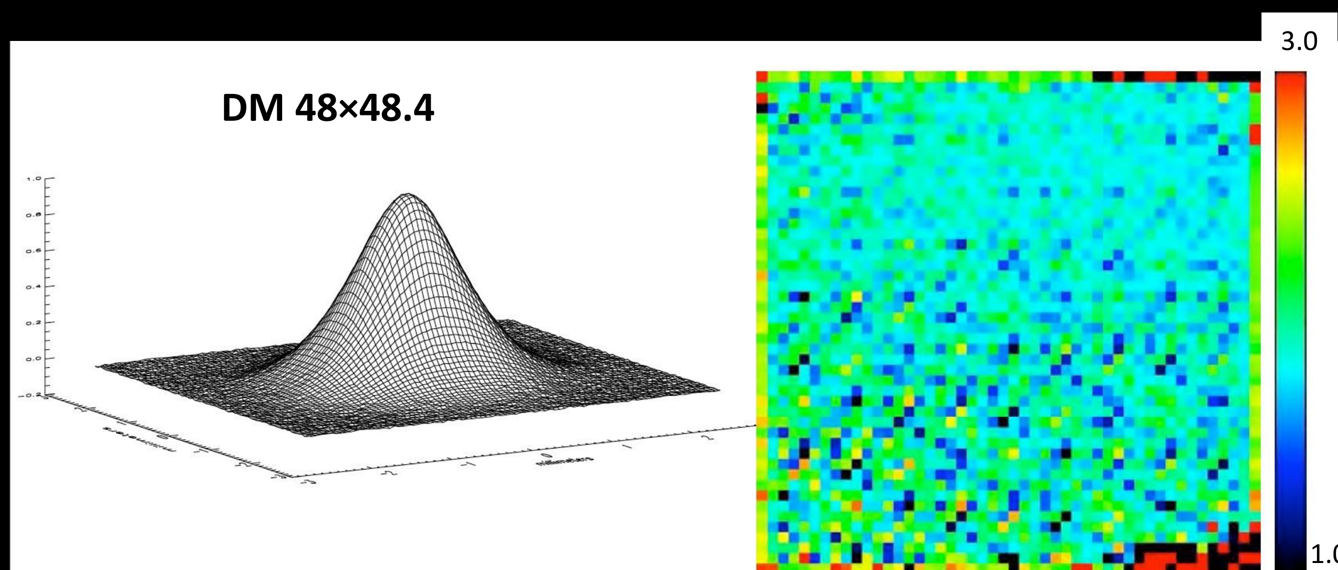
PMN Deformable Mirrors

Actuator characterization and calibration using the Vacuum Surface Gauge

- Facility for picometer-level characterization of actuator accuracy and stability
- Development of flight DM requirements
- Optimization of face-sheet thickness for maximum stroke length
- Support for performance modeling and Wavefront control model
- Characterization before /after environmental testing (flight qualification)
- Flight DM acceptance testing
- Three new DM’s delivered by Xinetics have been characterized on VSG prior to integration into HCIT

Packaged 48×48 DM, Xinetics

Measured influence profile (left); Free stroke/single actuator stroke ratio (right)



CGI Technology Milestone 7

Technology Milestone 7 was passed in Sept 2016

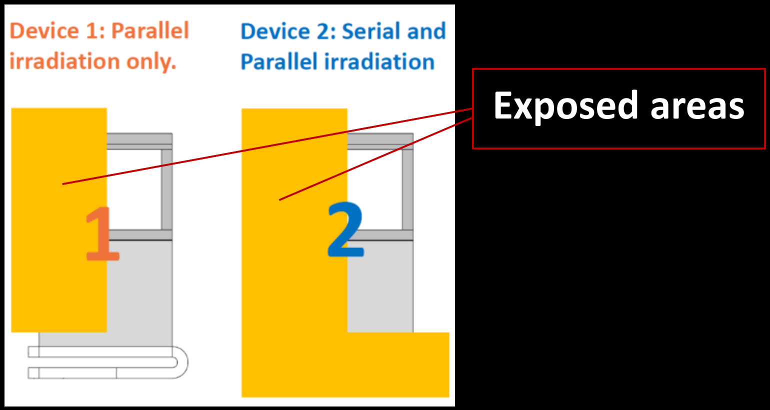
- EMCCDs were exposed to high energy protons at room temperature and at cryo-operating temperatures
  - Displacement Damage Dose was consistent with 6 year life in an L2 orbit
  - Radiation Design Factor of 2 means dose includes 100% margin
- EMCCD meets MS-7 low noise requirements at Beginning of Life (BOL) & at End of Life (EOL)
- In addition to dark current and read noise, many other performance parameters were characterized and showed acceptable degradation after radiation exposure

EMCCD (e2V CCD201-20) satisfies MS-7 criteria

Parameter	Units	Org.	Pre-Irradiation	Post-Irradiation 2.5×10^9 pr/cm^2	MS-7 Requirement
Image area Dark Current	e-/pix/sec	JPL	$(3.00\pm0.40)\times10^{-5}$	$(7.00\pm0.50)\times10^{-4}$	1.0×10^{-3}
Effective Read Noise	e-/pix/frame	JPL	1.70×10^{-6}	1.70×10^{-6}	1.0
Total CIC	e-/pix/frame	JPL	$(2.1\pm0.2)\times10^{-3}$	$(2.3\pm0.2)\times10^{-3}$	—

EMCCD Low Flux Detection

Low flux imaging lab was built to demonstrate detection of ultra-low flux PSF at



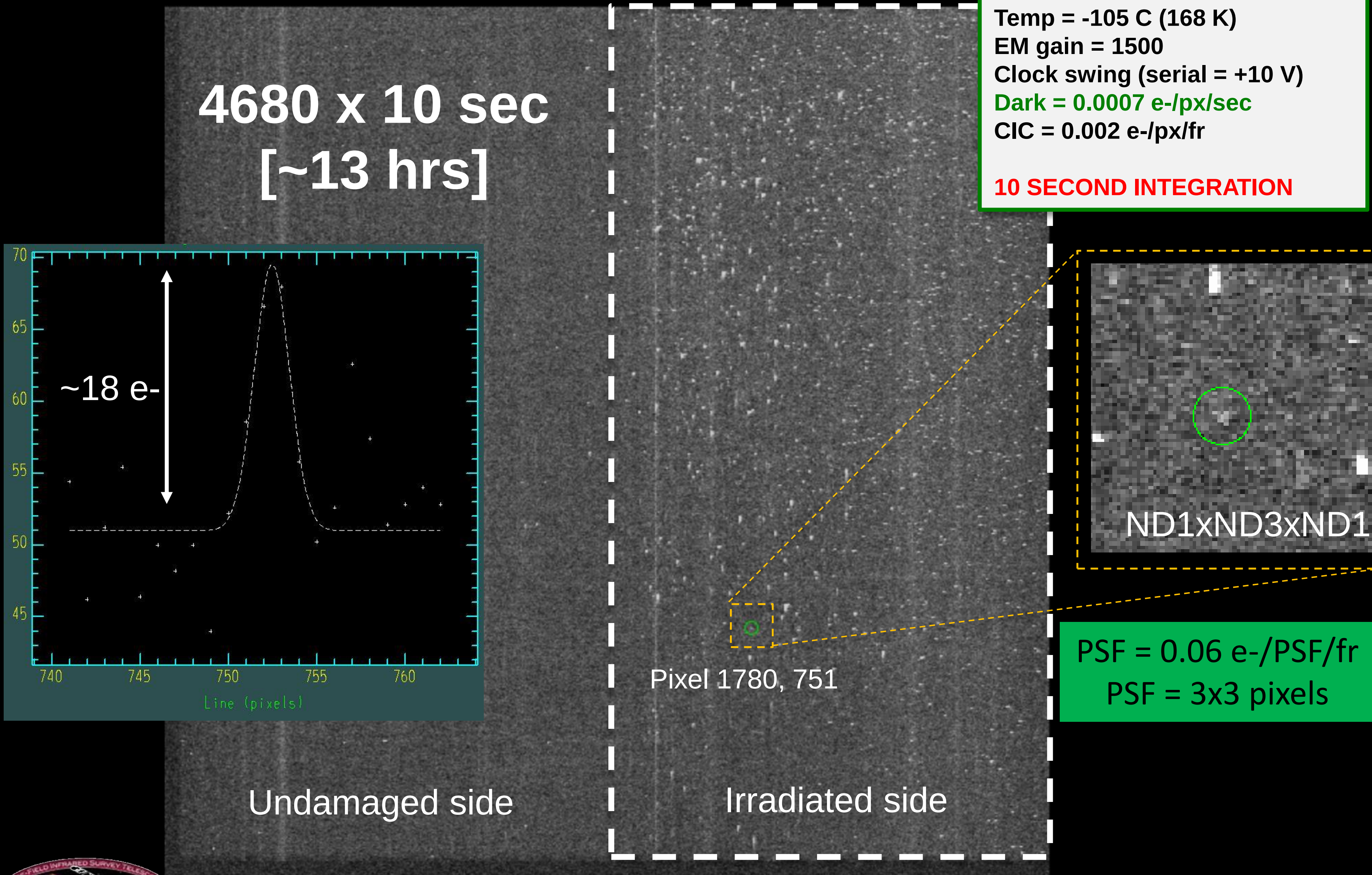
1. Beginning of life (BOL) and
2. After radiation damage (2.5×10^9 pr/cm^2)

- Demonstrated so far
  - *Beginning of life* – 0.02 e-/PSF/frame for 3×3 pixel PSF
  - Equivalent to detection of a 35th magnitude star using WFIRST telescope without the coronagraph
  - *Radiation damage >6 years at L2* – 0.06 e-/PSF/frame for 3×3 pixel PSF
- The lower limit of detection capability is yet to be determined
- Ultimate performance at end of 6 year mission is not yet quantified

PSF Measurement – 2.5 x 10^9 pr/cm^2

Temp = -105 C (168 K)
EM gain = 1500
Clock swing (serial = +10 V)
Dark = 0.0007 e-/px/sec
CIC = 0.002 e-/px/fr

10 SECOND INTEGRATION



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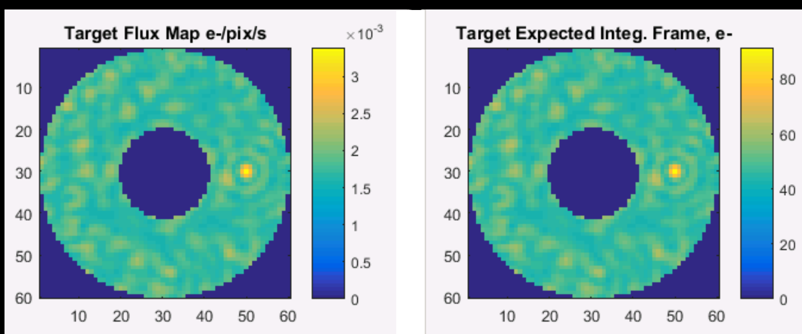
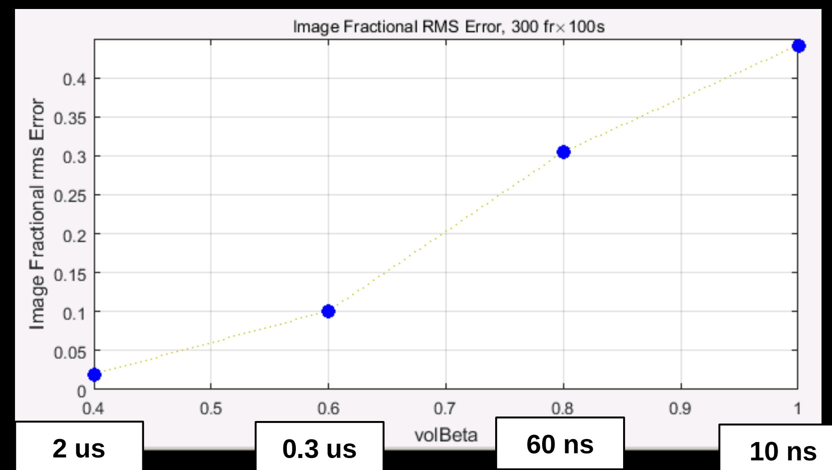
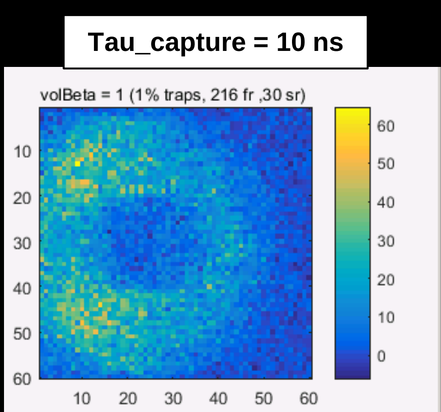
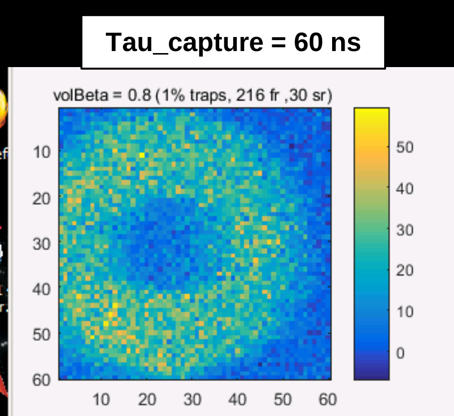
EMCCD Trap Modeling

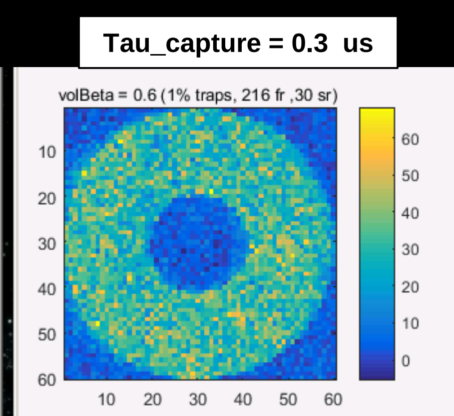
- Model of image degradation due to defect induced traps was developed
  - Can simulate both the imaging and IFS cameras
- Photometric model of CGI planet detection yield has been developed incorporating detector parameters as well as CGI parameters

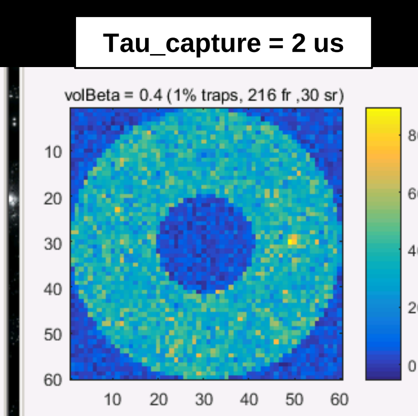












CGI Technology Summary

- Significant progress achieved on Technology Milestones
  - Reports submitted to NASA for Milestones 8, 9; TAC review 8 Nov
  - Milestone 7 passed, Sept 2016
- Successfully carried out OMC LOWFS/C dynamic test program
  - Pointing error suppression
  - Low order wavefront drift rejection with deformable mirror
- Contrast model in reasonable agreement with test-bed
- Coronagraph lithographic masks passed environmental testing
- PISCES IFS successfully integrated into Shaped Pupil Test-bed and calibrated
- Deformable mirror characterization matured to 10's picometer accuracy
- Ultra Low flux PSF's detected in radiation damaged EMCCD

DARE MIGHTY THINGS

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jpl.nasa.gov

RESERVE SLIDES

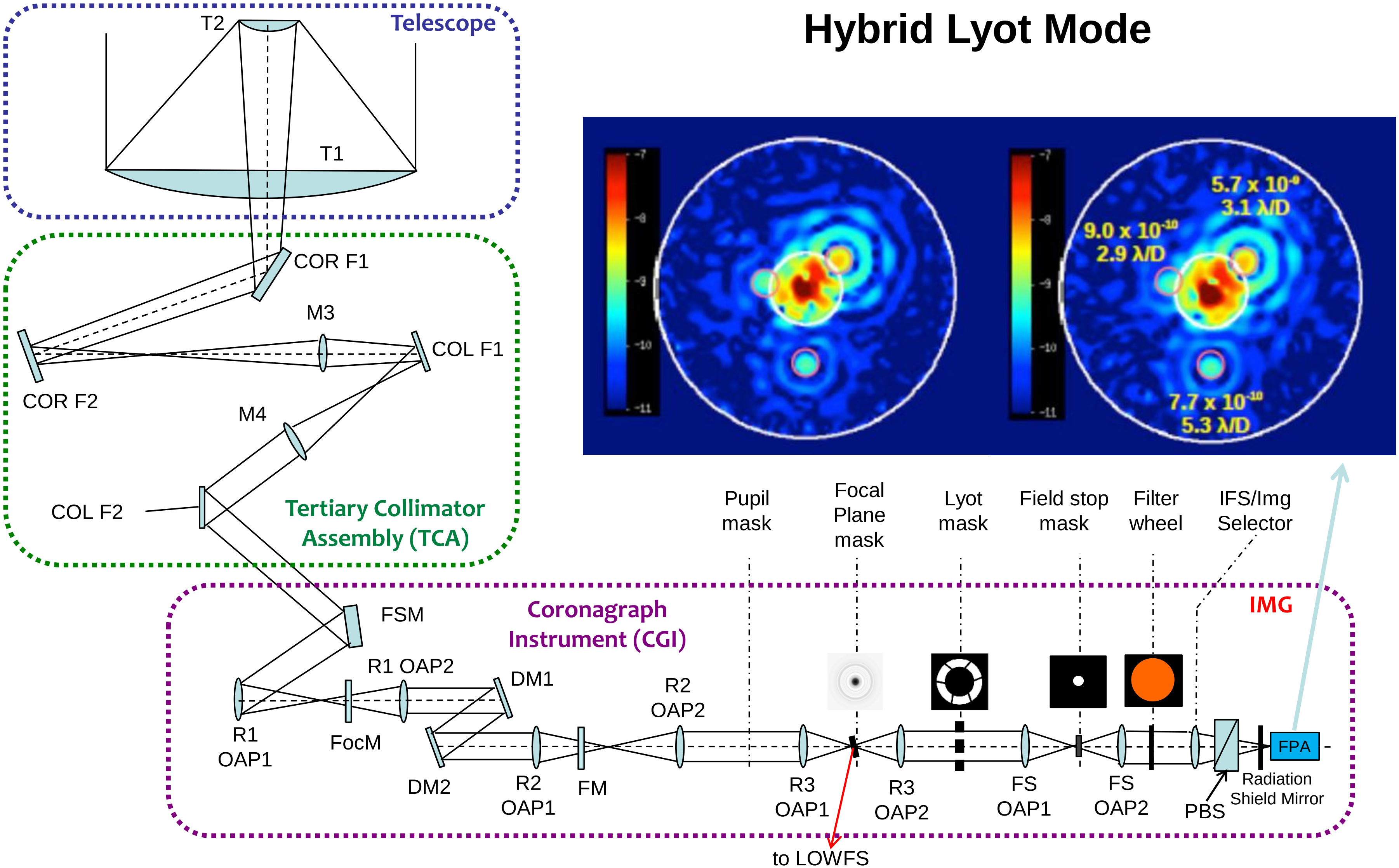
WFIRST Coronagraph Team

Coronagraph partner institutions:

- NASA GSFC (provided test-bed integral field spectrograph)
- NASA ARC (supporting backup technology PIAA-CMC)
- Science Centers:
  - IPAC/Caltech, STScI

CGI Operational Modes

Hybrid Lyot Mode



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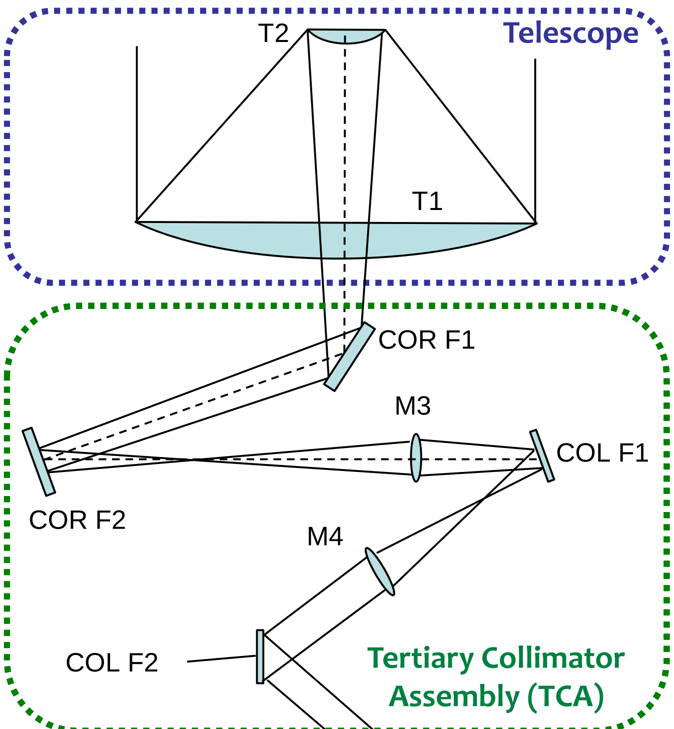
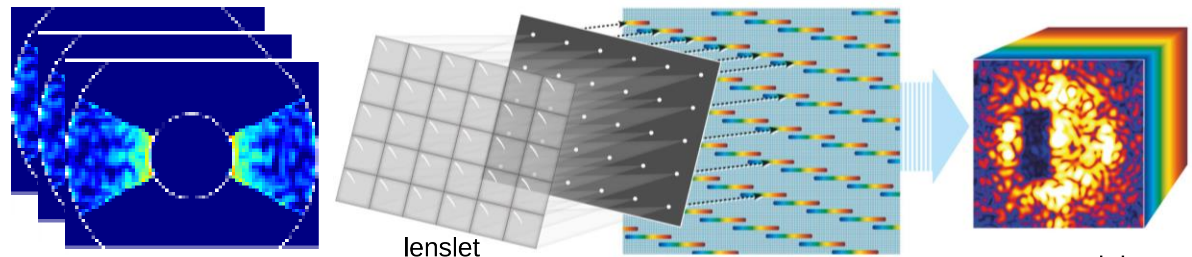
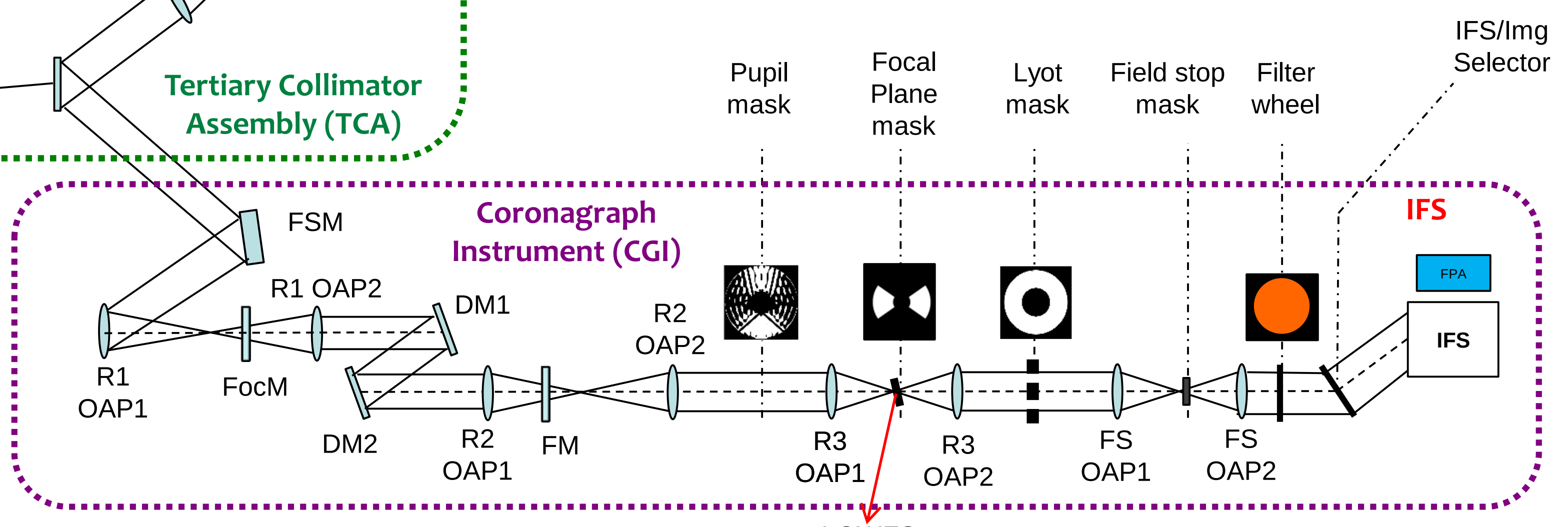
CGI Operational Modes



Shaped Pupil Spectroscopy Mode

The IFS uses 3 18% bands to produce an R=70 spectra from 600 to 970 nm



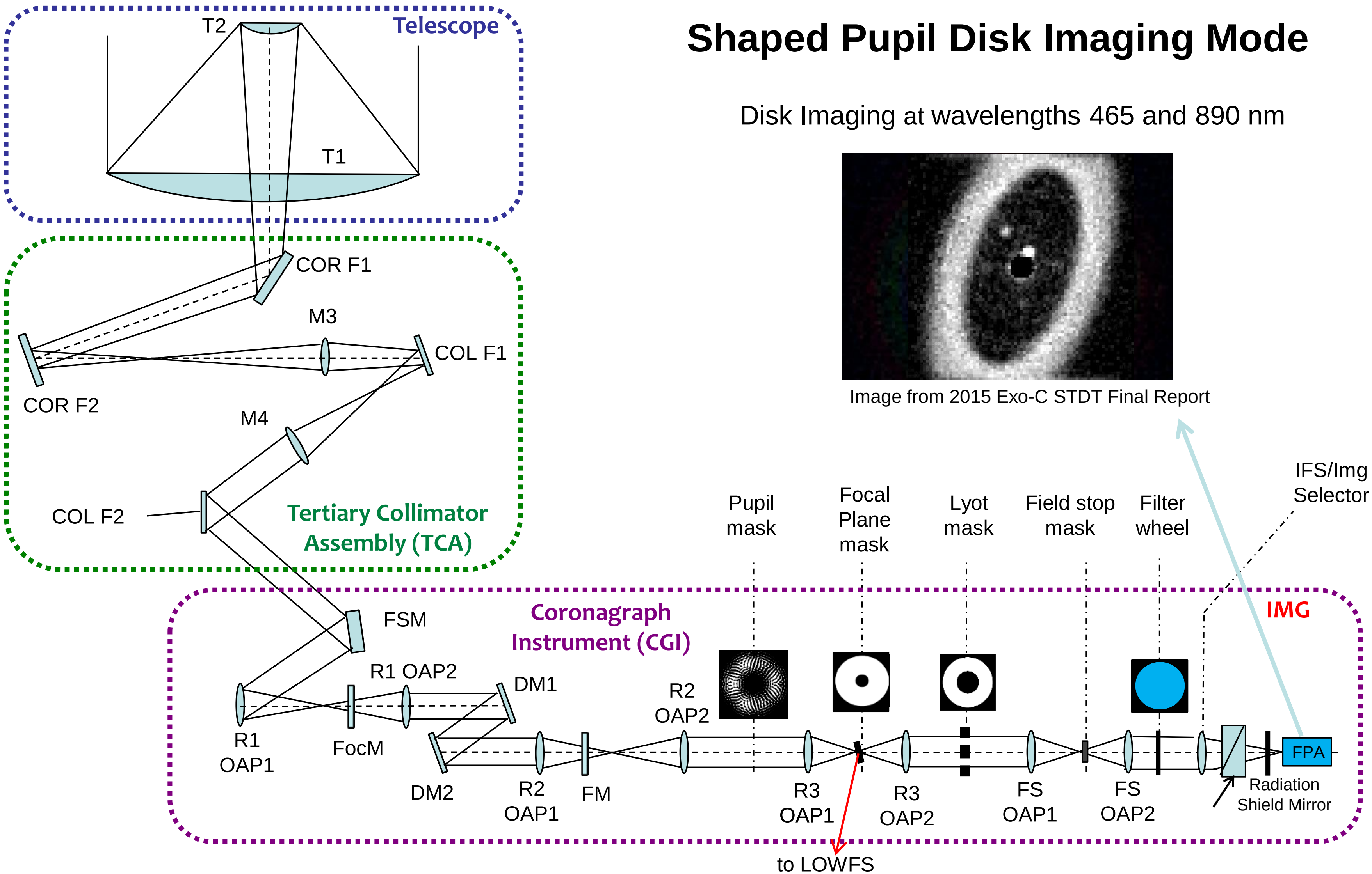


CGI Operational Modes

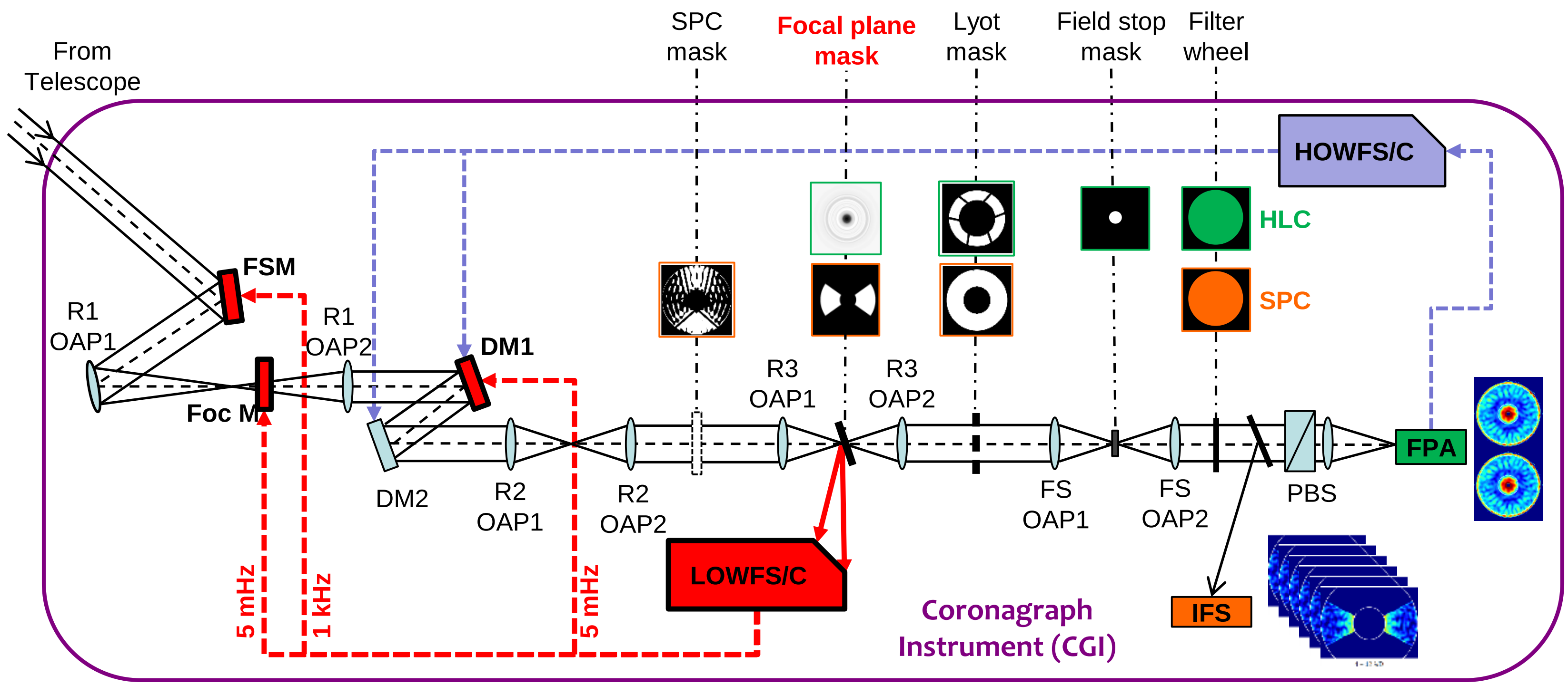
Shaped Pupil Disk Imaging Mode

Disk Imaging at wavelengths 465 and 890 nm

Image from 2015 Exo-C STDT Final Report



Low Order Wavefront Sensing & Control



LOWFS/C subsystem measures and controls line-of-sight (LoS) jitter/drift and low order wavefront drift (also measures low order wavefront jitter)

- Uses rejected starlight
- Differential sensor referenced to coronagraph wavefront control: maintains wavefront established for high contrast
- Telemetry can be used for post-processing

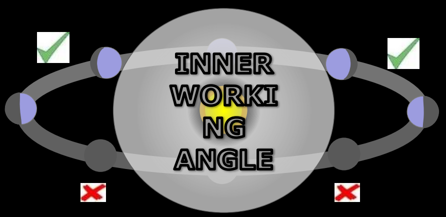
Orbits, Traps and Coronagraphs

- In general the planet is only viewable about 1/3 of the time. At the same time, the typical RV candidate will have an 8 year orbital period.

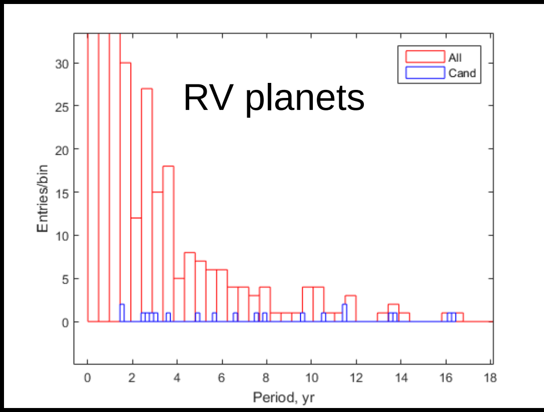
- One consequence is that planet observations will necessarily be interspersed throughout the mission lifetime.
  - Some will see a new detector
  - Some will see a detector with traps

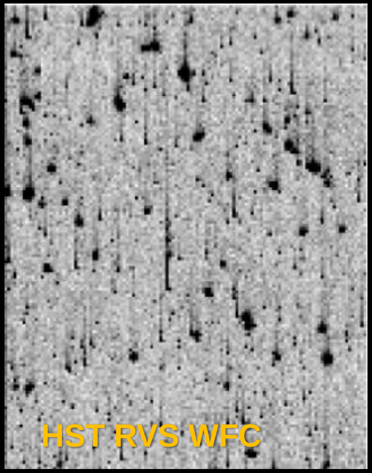
- In a CCD, where the parallel clocking process transfers the charge from one row to the next all the way to the readout ("serial") register, the effect of traps is exacerbated since each trap influences signal from upstream pixels in the same column.

- In direct imaging, where we are dealing with objects as dim as 30+ mag, things get even more challenging:
  - Photo-electron rates are at the milli-electrons per second level, so need to integrate a long time to get a signal at all
  - On the other hand, cosmic rays limit exposure times to order 1000 s



the planet will be observable only ~ 1/3 of the time





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Backup Detector Trade

Leading Alternatives to EMCCD

- Modified EMCCD for radiation hardening
  - Reduced channel width in readout chain and image pixels
  - Improves image degradation due to traps but doesn't mitigate CRs
  - Will ask e2V for insight on CR-hard designs

- Micro-channel plate detector with CMOS or CCD on backend
  - Low QE (~30% w/ GaAs) but large gain
  - Simpler drive electronics
  - Far less susceptible to traps and cosmic rays

- CMOS non-destructive readout detectors
  - Monolithic and hybrid silicon types
  - Easy to remove CR's
  - Very low flux readout capability is under investigation