WFIRST-AFTA Coronagraph Instrument

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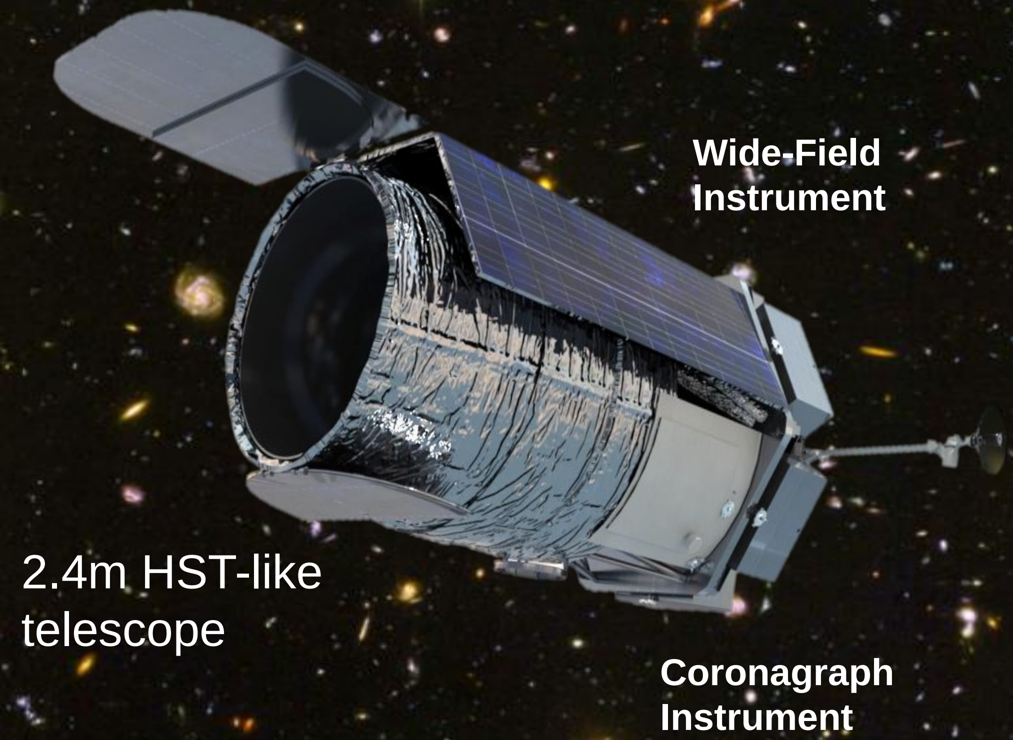
Jet Propulsion Laboratory
California Institute of Technology

2015–11–12

WFIRST-AFTA

Wide-Field Infrared Survey Telescope (WFIRST)
Astrophysics Focused Telescope Assets (AFTA)



WFIRST Definition

Existing Coronagraphs

How a coronagraph works

WFIRST capability

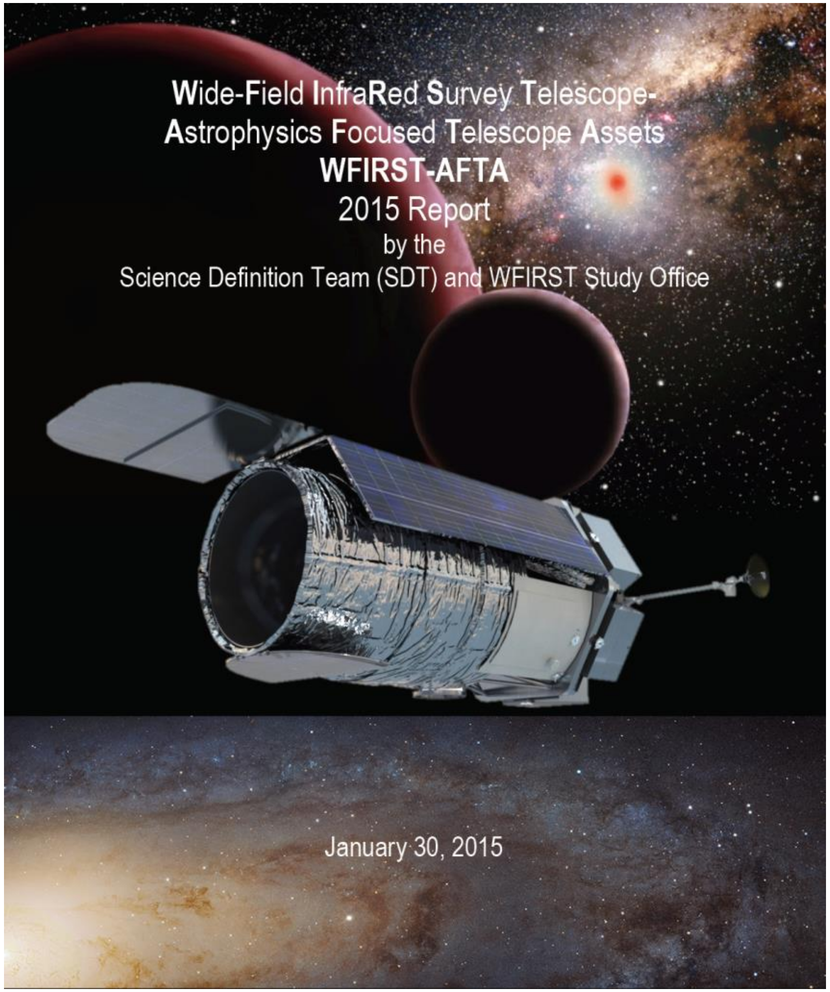
Challenges – how far beyond SoA?

Latest results & future effort

WFIRST coronagraph will develop the technologies for a future exo-Earth mission

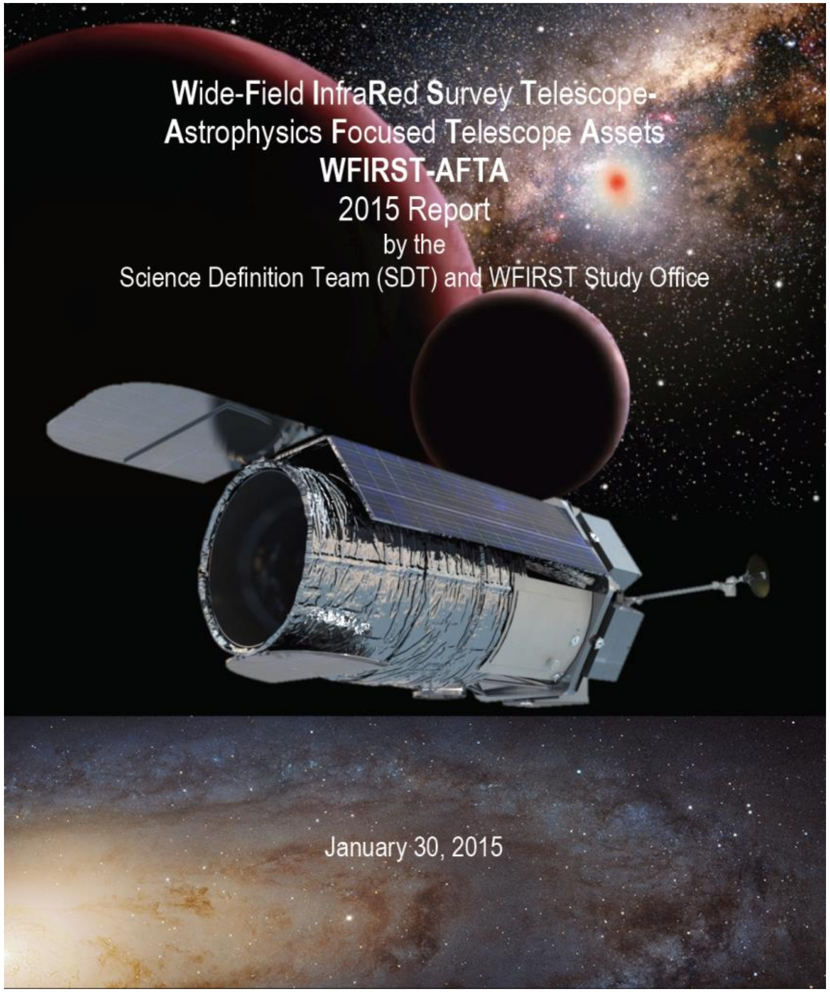
WFIRST-Coronagraph Instrument Study

- **Coronagraph Instrument (CGI) Design Reference Mission**
  - 2nd instrument on WFIRST, with possible 2016 Phase A start and 2026 launch
    - Technology demonstration of Exo-planet direct imaging
    - Pre-cursor science for future exo-earth missions
  - High contrast imaging using precision wavefront sensing and control



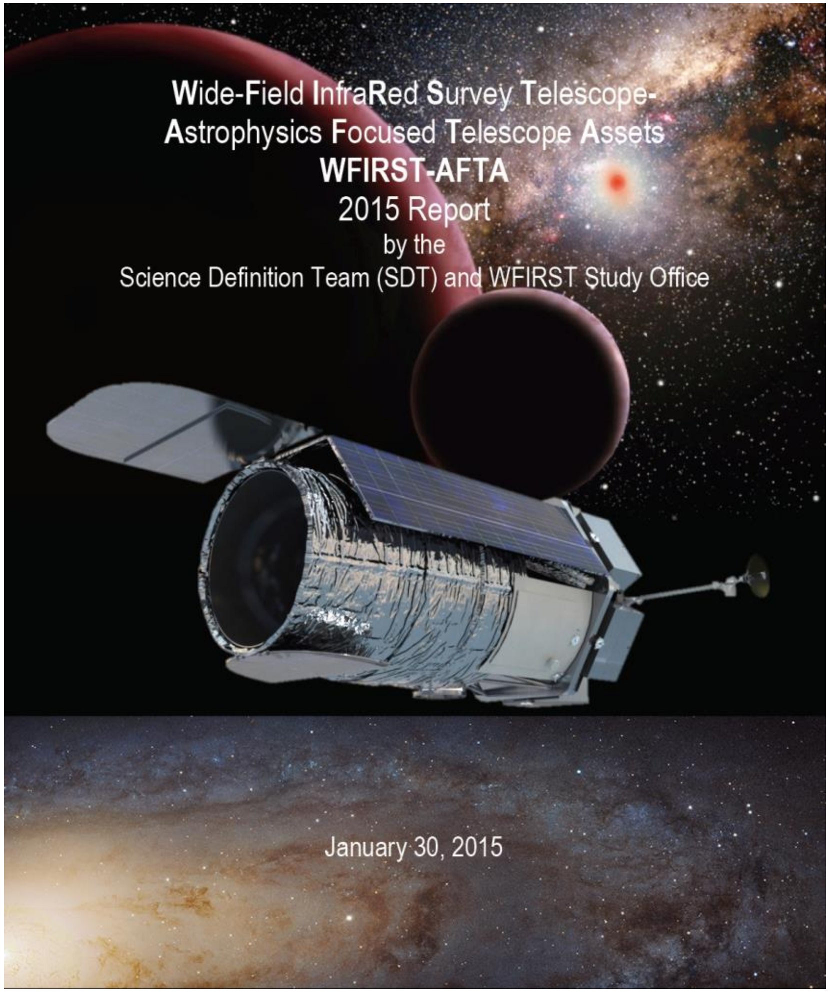
WFIRST-Coronagraph Instrument Study

- **JPL–led Technology Development Team**
  - Princeton University
  - University of Arizona
  - GSFC
  - Ames Research Center
  - STScI
  - Caltech/IPAC
  - Northrop-Grumman Xinetics



WFIRST-Coronagraph Instrument Study

- **Near-term Key Deliverables**
  - ✓ – SDT final report 01/2015
  - ✓ – CATE done in 02/2015
  - ✓ – Mass/power/cost consistent with existing flight analogs
  - – Mission Concept Review (MCR) 12/2015
  - – Technology completion by 12/2016
    - TRL-5 at instrument system level



JPL

Why a WFIRST Coronagraph?

HST Coronagraphs

- NICMOS NIR
- ACS V band (Fomalhaut disk)
- STIS UV-VIS (still operational)

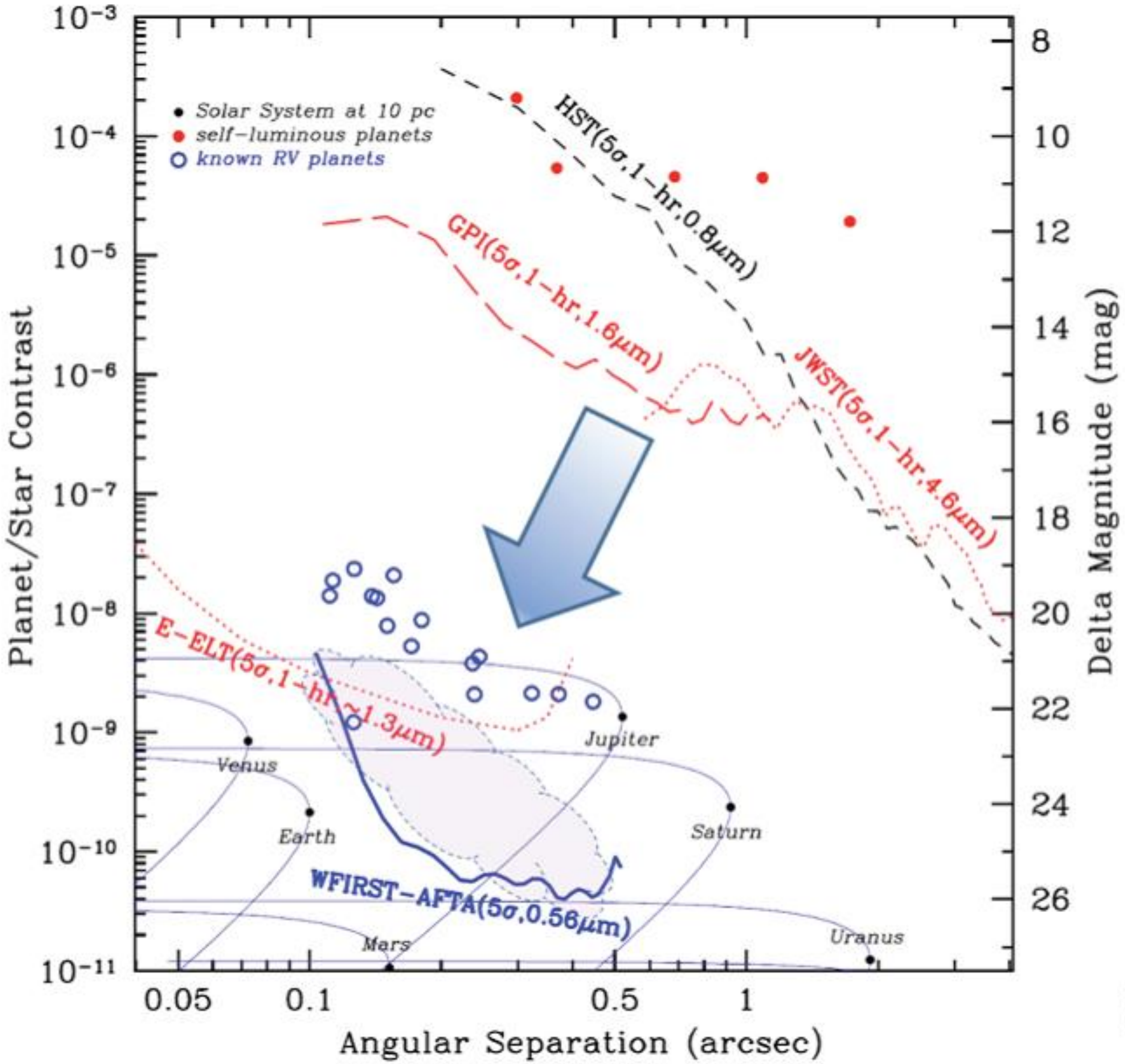
Inner Working Angles (IWA) inadequate for exoplanet detection

Ground-Based Coronagraphs

- GPI
- SPHERE
- Project 1640

-IR detection only

-Contrast insufficient for faint exoplanet detection (Jupiter, Earth analogs)



Coronagraph Instrument

Coronagraph Science Objectives:
Planet Imaging & spectral characterization
Dust debris characterization

- Utilizes the 2.4m aperture AFTA* telescope
- Advances the TRL of direct imaging instrumentation
- Uses technology based on the successful High Contrast Imaging Test-bed (HCIT)
- Technology Demonstration – Coronagraph does not drive WFIRST mission schedule or cost
- Two coronagraphs alternately operated within a single optical beam-train

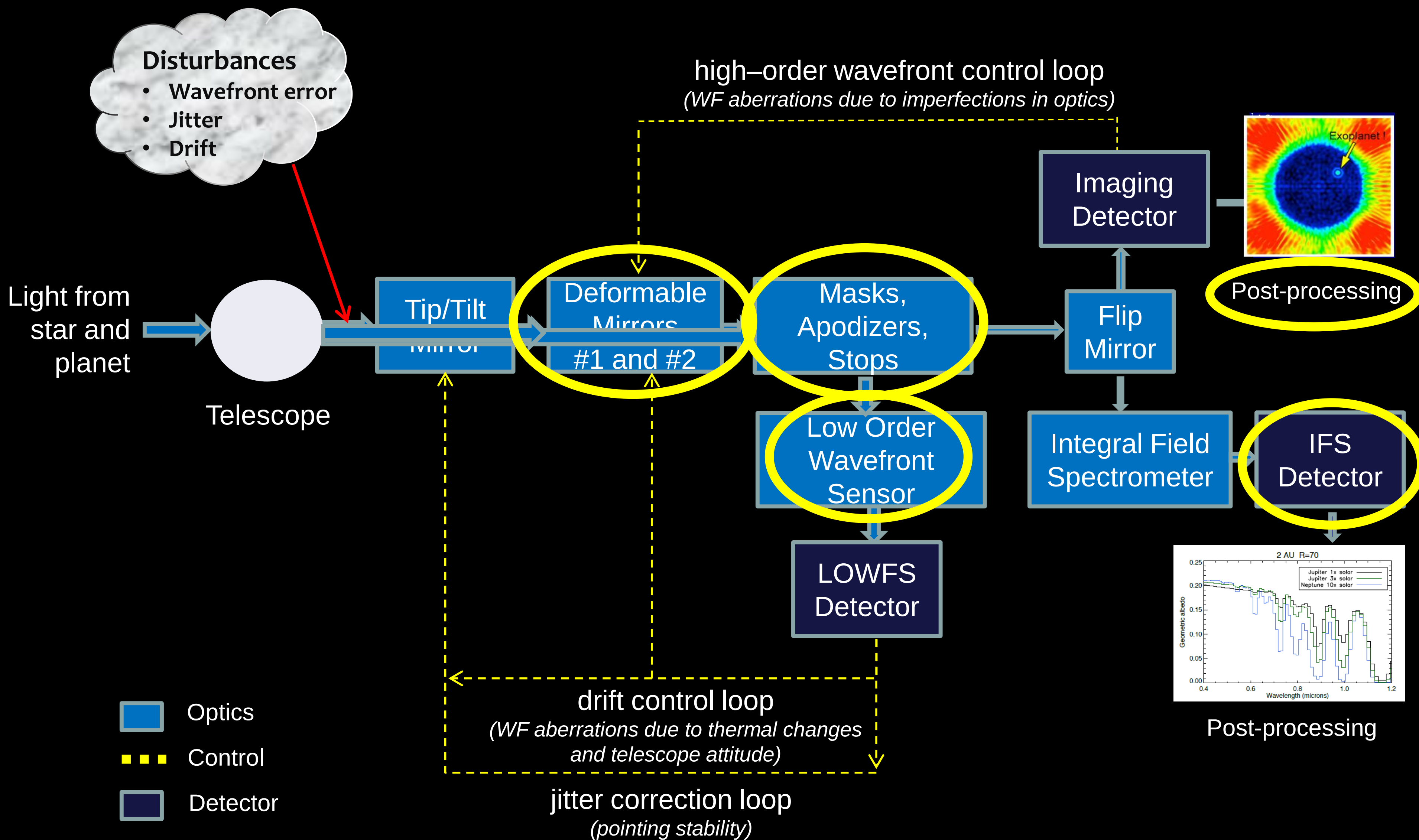
①Hybrid Lyot Coronagraph (HLC) – planet imaging

②Shaped Pupil Coronagraph (SPC) – planet spectroscopy & disk characterization

* Astrophysics-Focused Telescope Asset

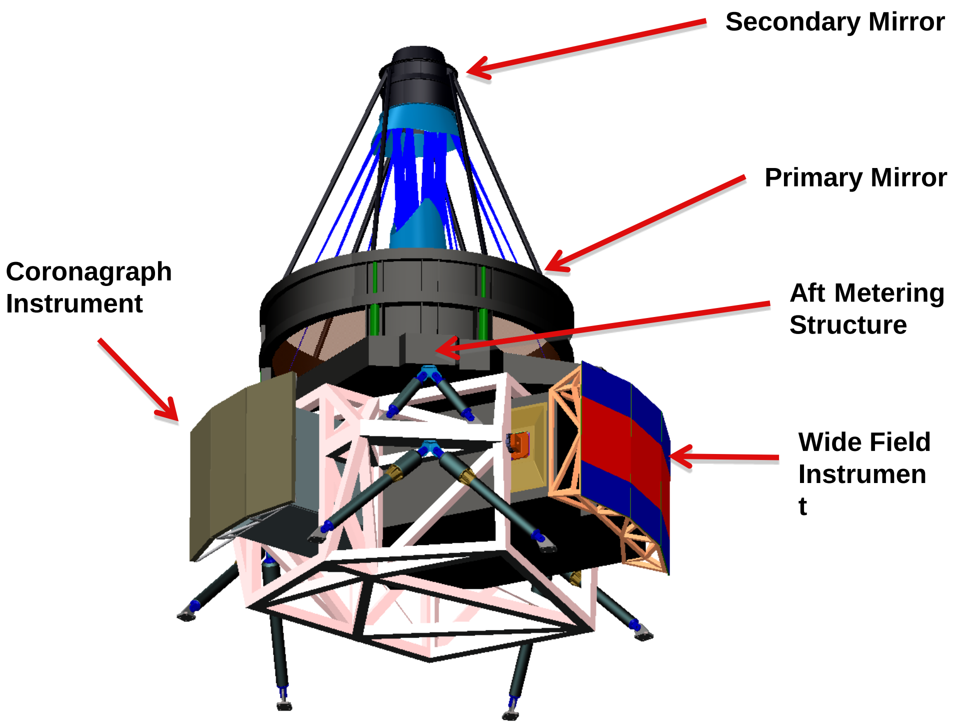
Bandpass	430 - 980 nm	Measured sequentially in 10% and 18% bands
Inner Working Angle [radial]	150 mas	at 550nm, 3λ/D driven by AFTA pupil obscurations
	270 mas	at 1μm
Outer Working Angle [radial]	0.5 as	at 550nm, 10λ/D, driven by 48×48 format DM
	0.9 as	at 1μm (imaging camera)
Detection Limit (Contrast)	10^{-9}	Cold Jupiters; deeper contrast unlikely due to pupil shape & extreme stability requirements.
Spectral Resolution	70	R = λ/δλ (IFS)
IFS Spatial Sampling	17 mas	3 lenslets per λ/D, better than Nyquist

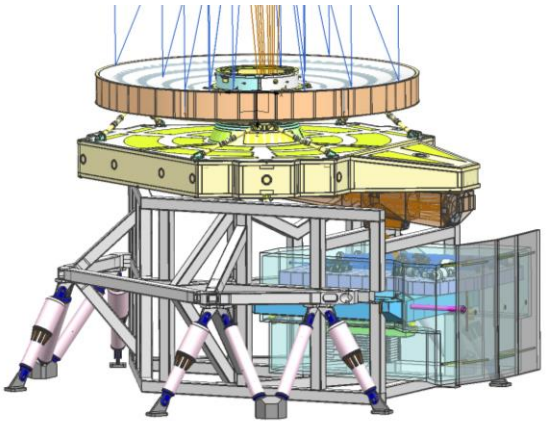
Block Diagram of a Lyot Coronagraph



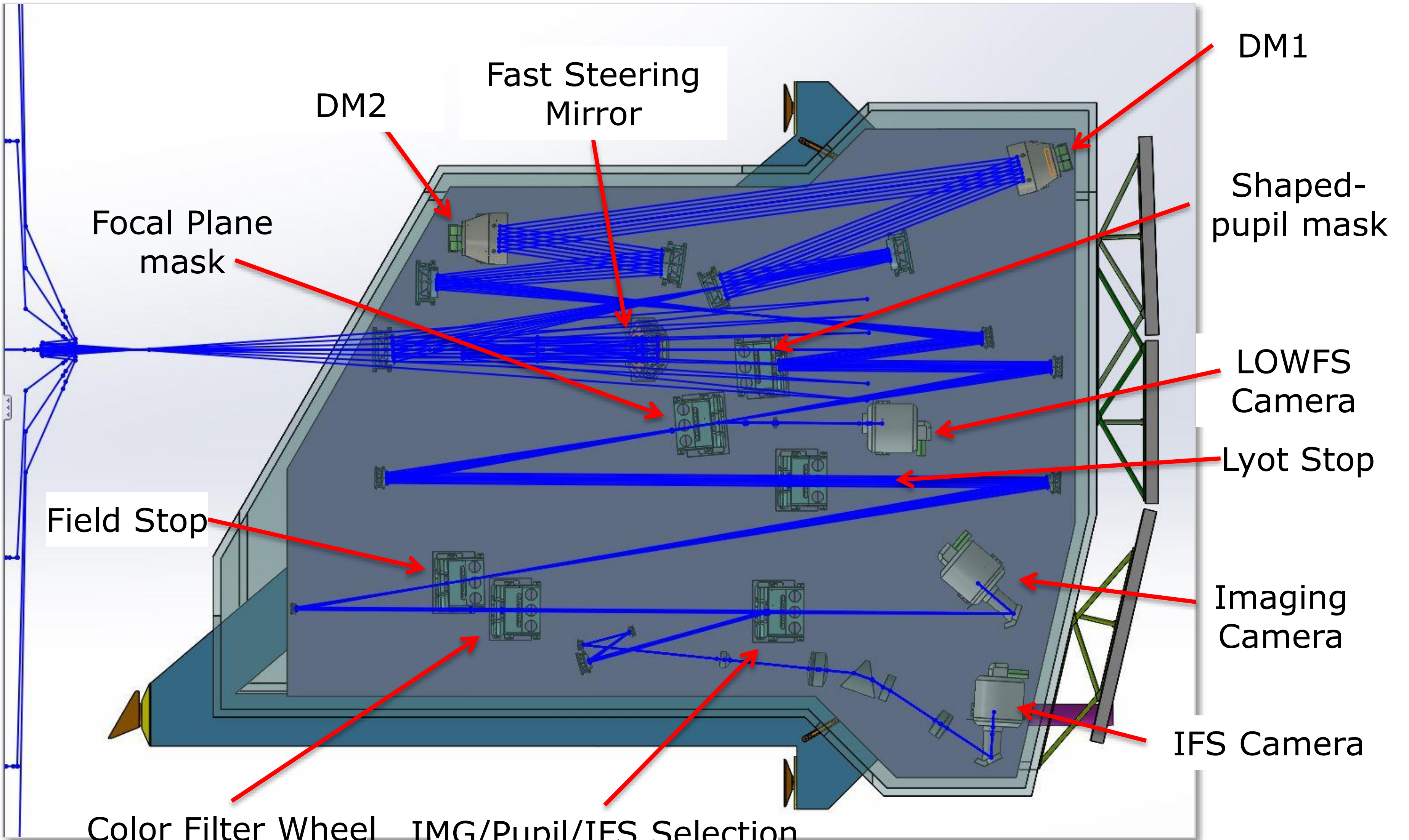
CGI Cycle 6 Design Summary

1. Coronagraph is designed for high thermal stability
2. All coronagraph core optics in one optical plane on a single bench
3. Horizontal latches for robotic instrument servicing
4. Passively cooled by 3 radiators (heat pipe for electronics, straps for focal plane arrays and focal plane electronics)



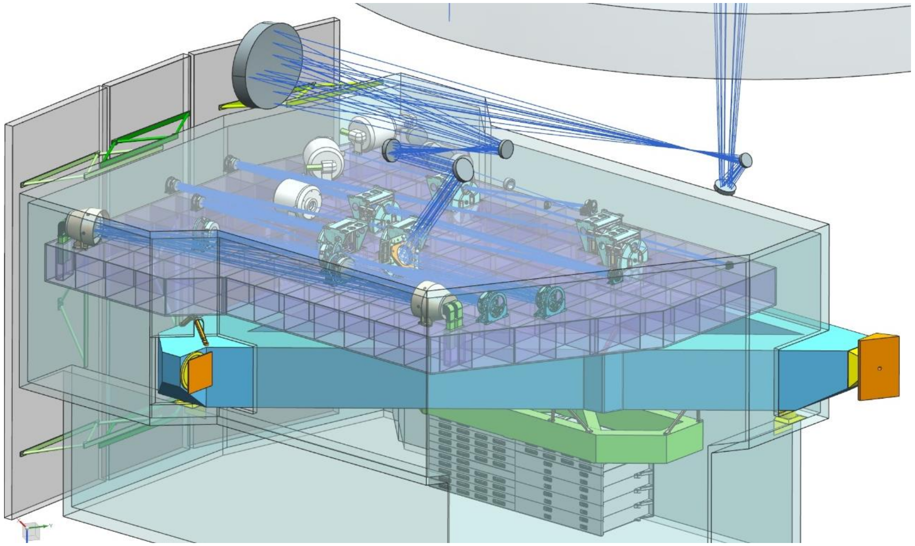


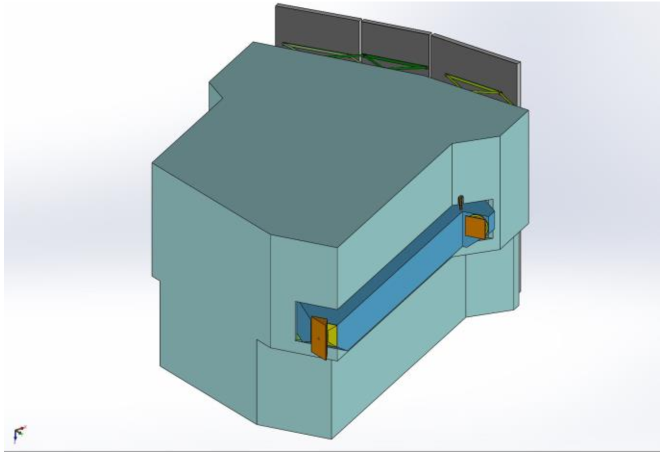
CGI Optical configuration

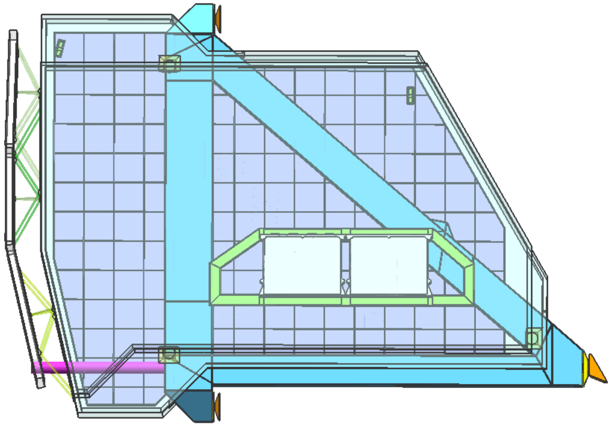


CGI Mechanical configuration

WFIRST-AFTA DRM Cycle 6



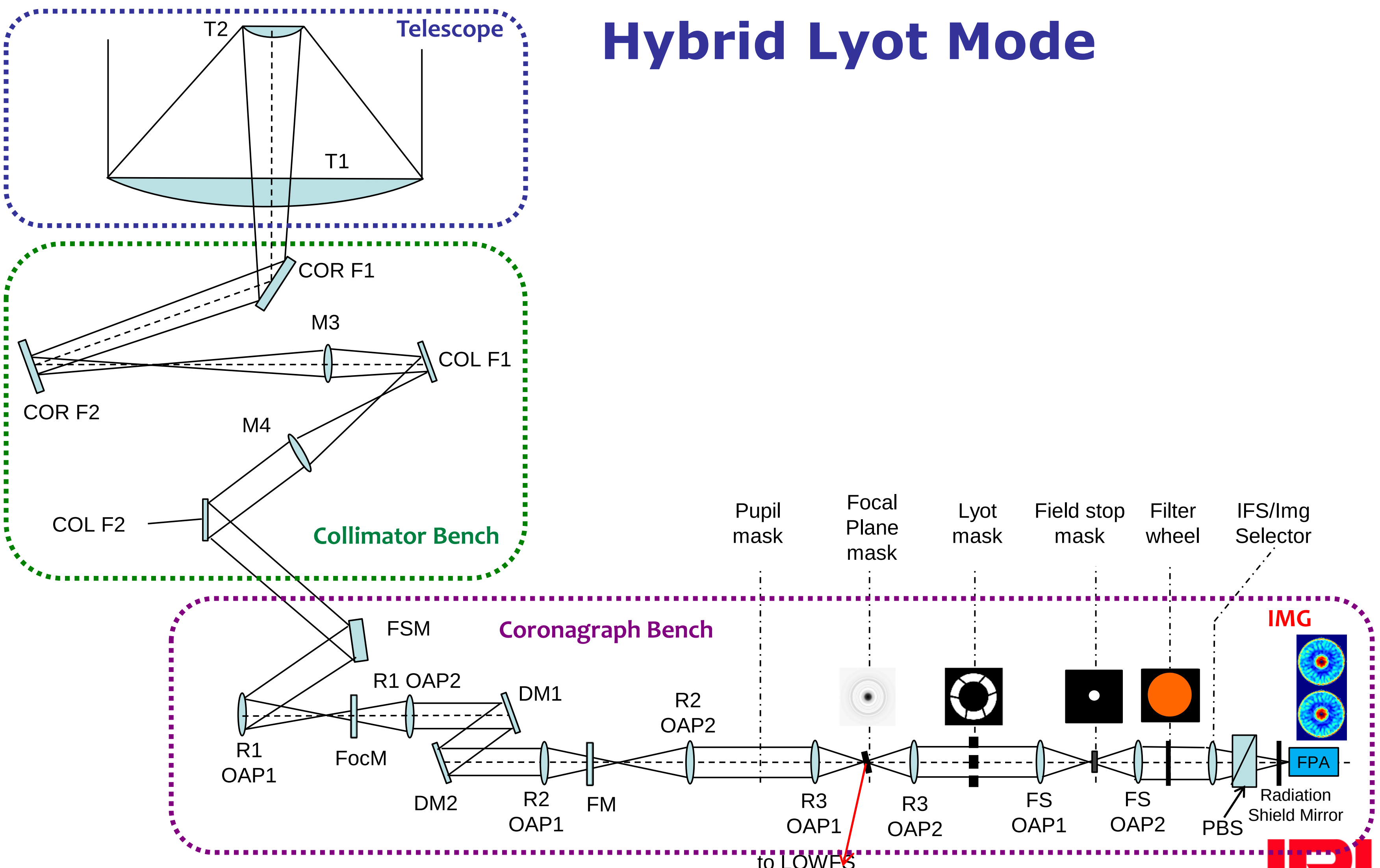




- Triangular composite box beam
  - Primary structure for the CGI instrument
  - Mounts the 3-2-1 latches in a horizontal plane to IC interface
- Main optical bench
  - Sandwich construction with face sheets of K13C2U isotropic
  - Composite for high stiffness and good heat transfer to minimize
  - Attaches kinematically to the triangle
- Electronics platform
  - Kinematic attachment to underside of triangle to minimize heat transfer to rest of instrument
- Thermal shroud
  - Composite sandwich construction for high stiffness, minimum weight
  - Supports radiators

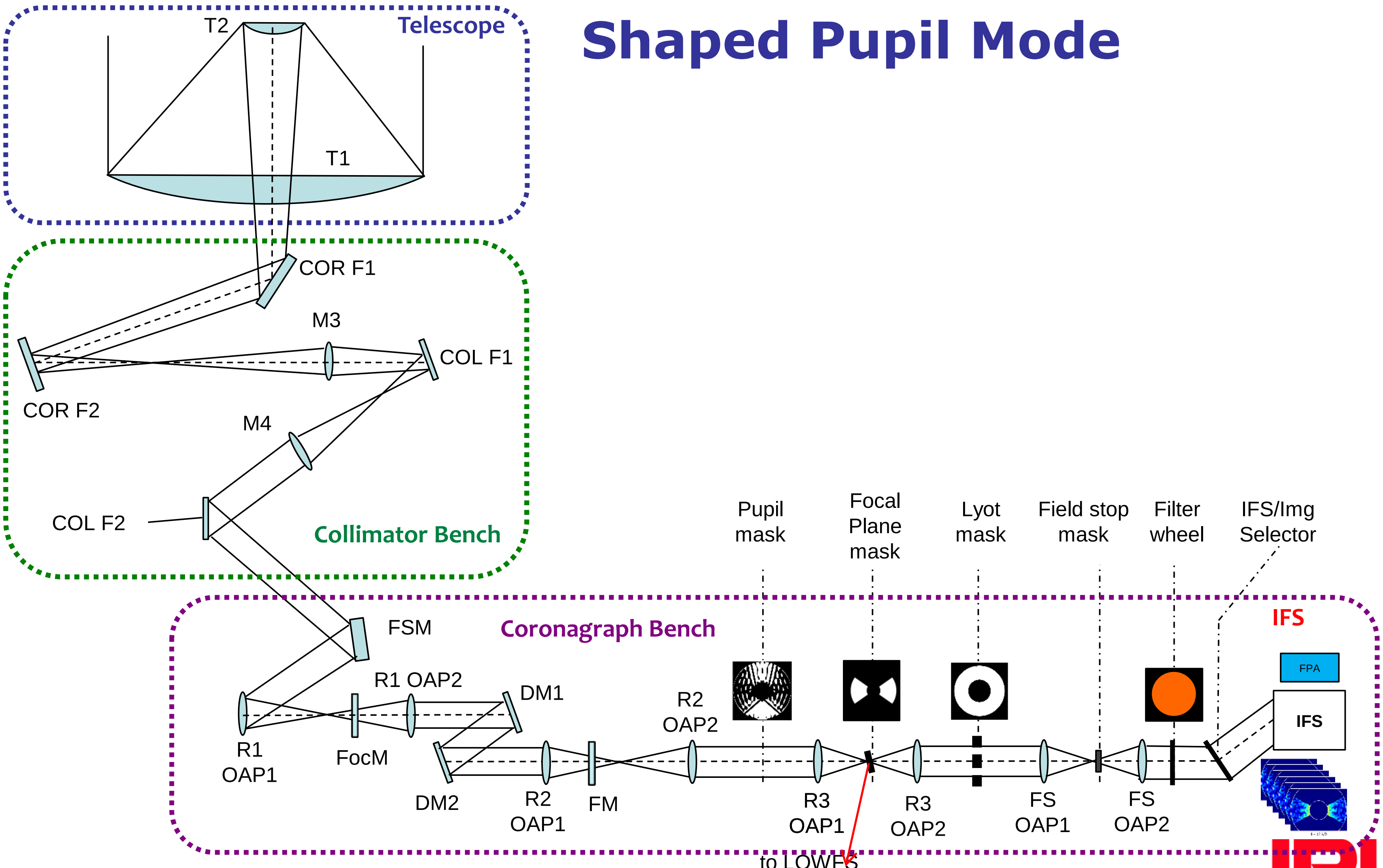
CGI Instrument Operational Modes

Hybrid Lyot Mode

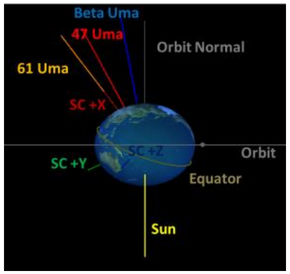


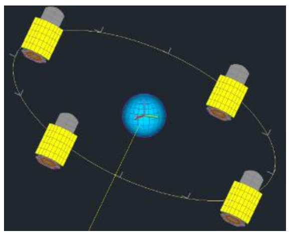
CGI Instrument Operational Modes

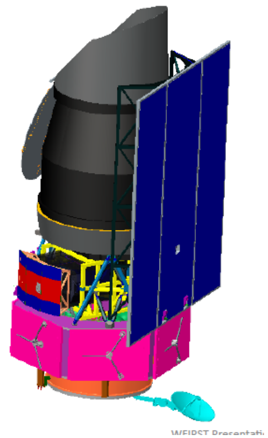
Shaped Pupil Mode

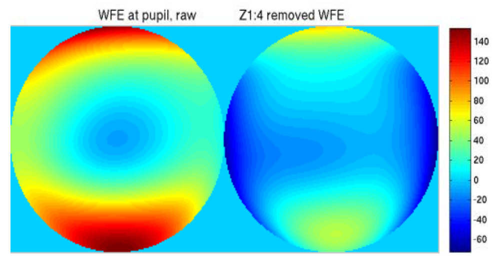


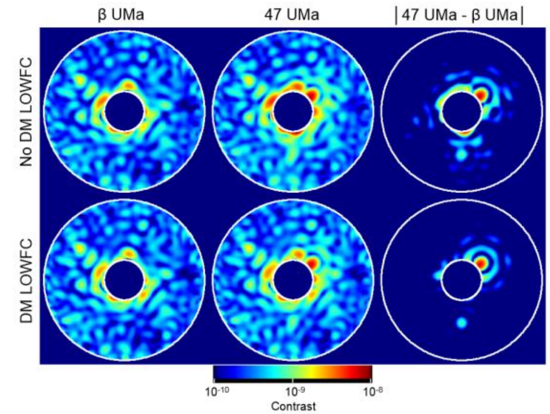
Detailed full-physics simulations to validate coronagraph with WFIRST-AFTA



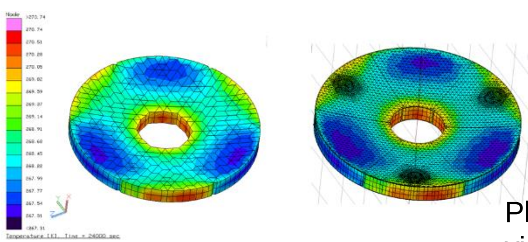




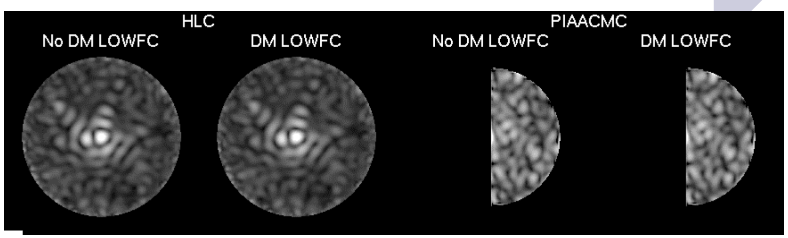




Scenario Defined → Thermal Loads → Structural Deformations → Ray Trace (Sig-Fit + Code V) → Exit Pupil WFE → DM Control (EFC) → Coronagraph (PROPER) → Images/Spectra



Play video here



Initial simulations indicate that the coronagraph is likely to achieve all performance goals with the current, unmodified telescope.

WFIRST-Coronagraph Challenges

1. **Higher contrast in the presence of disturbances**
   - Thermal drift
   - Vibration induced jitter

2. **Accurate correction for wavefront error**
   - DM calibration must be at picometer level

3. **Detector degradation due to radiation**
   - Charge traps distort the point spread function (PSF)

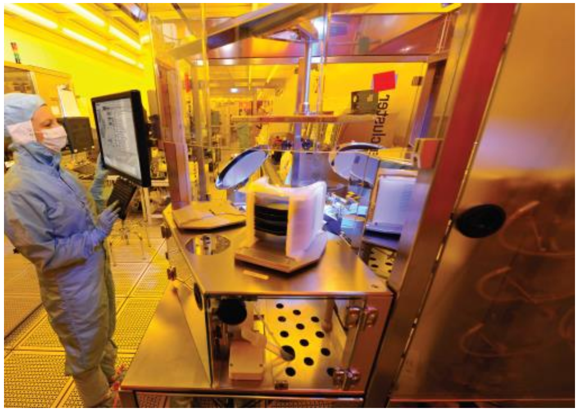
WFIRST-AFTA Coronagraph Key and Controlled Milestones

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

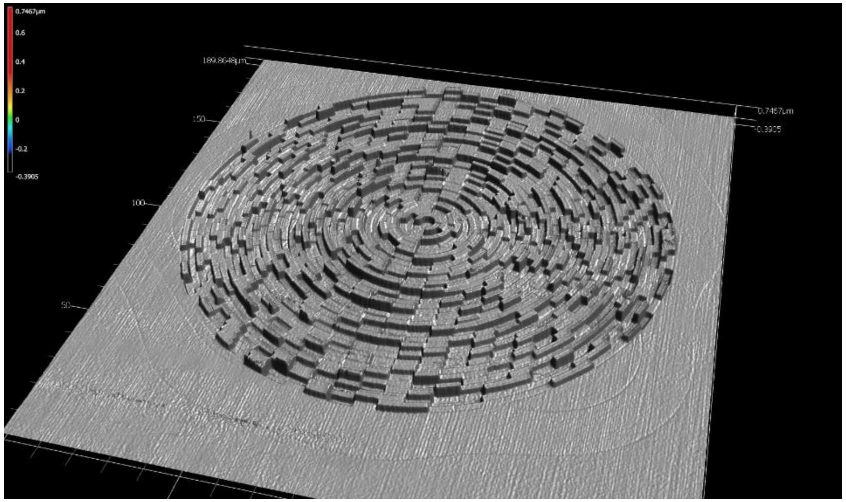
FY15

WFIRST Coronagraph 2015 Accomplishments: Milestone #3

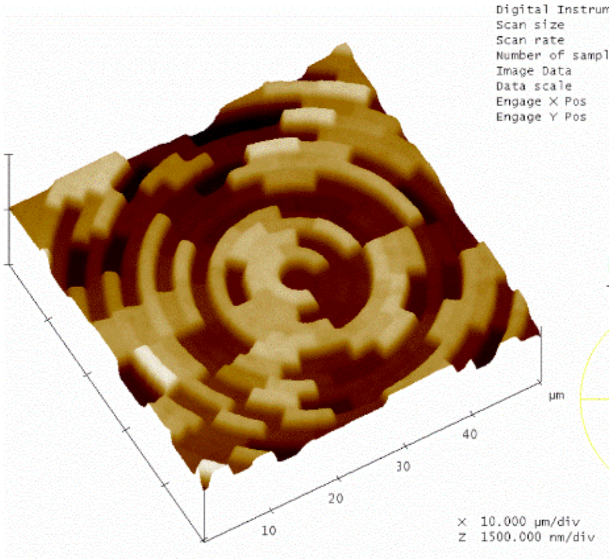
- PIAA-CMC (Phase Induced Amplitude Apodization Complex Mask Coronagraph) mask fabricated and characterized at JPL's Micro Devices Lab
- Technical Assessment Committee (TAC) reviewed PIAA-CMC mask result on 12/15/2014. TAC unanimously passed technology Milestone #3!



MDL E-beam facility at JPL



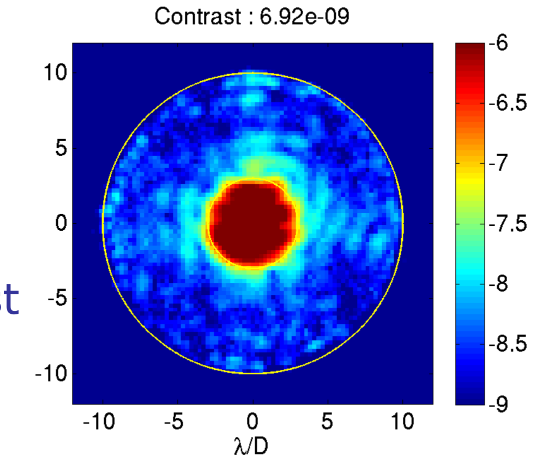
PIAACMC mask image with a laser confocal microscope



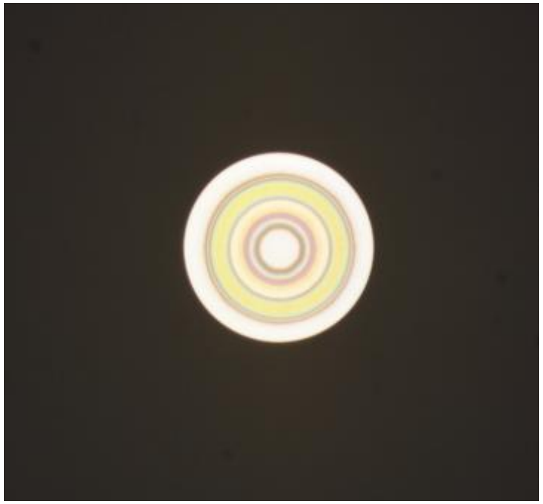
PIAACMC mask image with an atomic force microscope

WFIRST Coronagraph 2015 Accomplishment: Milestone #4

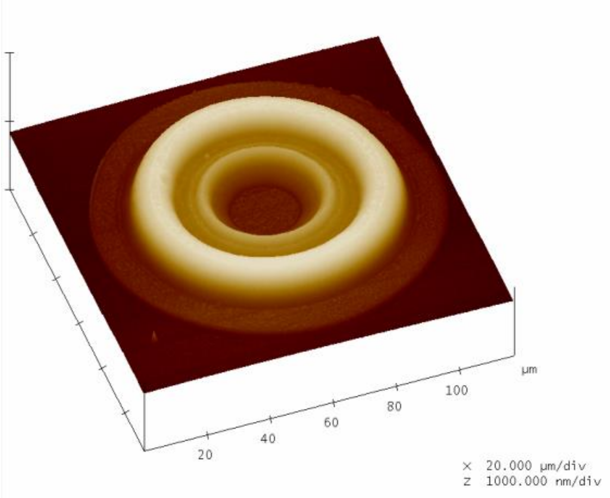
- HLC (Hybrid Lyot Coronagraph)
  - HLC occulter mask made with E-beam lithography at Micro Devices Laboratory at JPL
  - AR-coated fused silica substrate, Ni dots, profiled dielectric (PMGI -- Polymethylglutarimide)
  - Milestone #4 (HLC narrowband exceeded 10^{-8} contrast requirement) passed TAC (Technical Assessment Committee) review on 3/13/2015!



HLC narrowband result: 6.9×10^{-9}



HLC occulter optical microscope image



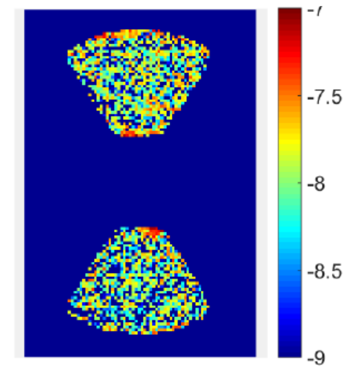
Atomic force microscope image

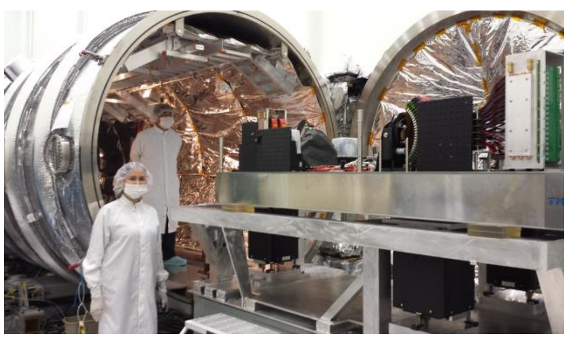
JPL

WFIRST Coronagraph 2015 Accomplishment: Milestone #5

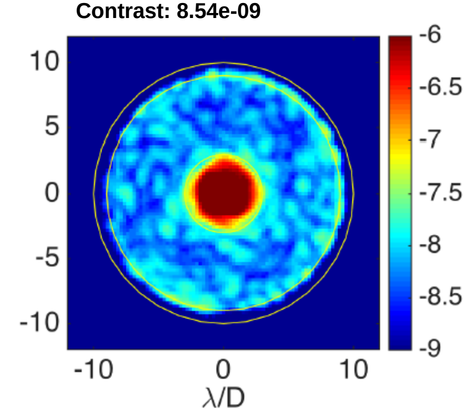
- Primary coronagraph architecture (Occulting Mask Coronagraph – OMC) consists of two designs:
  - HLC (Hybrid Lyot Coronagraph)
  - SPC (Shaped Pupil Coronagraph)
- Demonstrated broadband (10% at 550nm) high contrast (<10^{-8} requirement) for both designs
- Milestone #5 passed TAC (Technical Assessment Committee) review on 9/29/2015

SPC: 10% bandwidth 550nm
Contrast: 7.98e-09





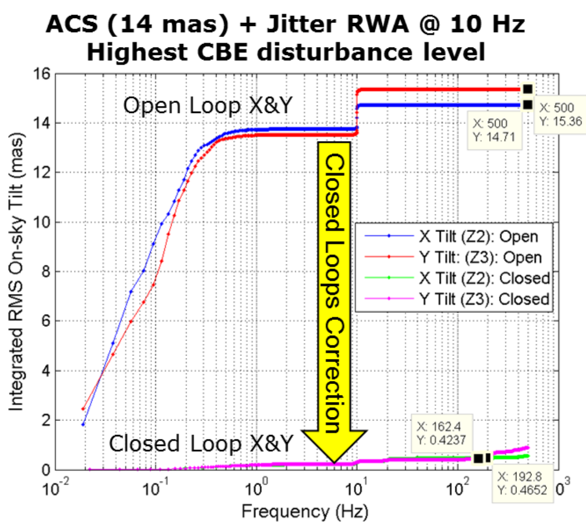
HLC: 10% bandwidth 550nm
Contrast: 8.54e-09

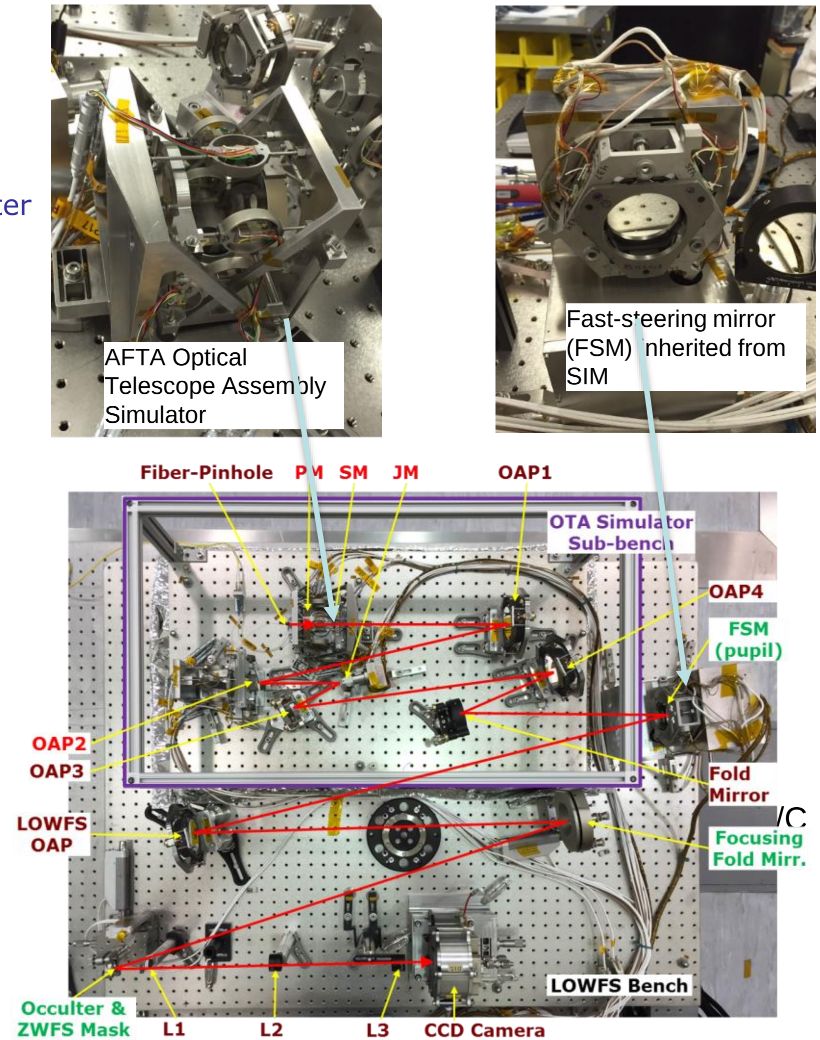


High contrast broadband demonstration with AFTA pupil!

WFIRST Coronagraph 2015 Accomplishment: Milestone #6

- Low-Order Wavefront Sensing and Control (LOWFSC) - a key enabling technology for coronagraph working with as-built telescope
- Based on Zernike phase contrast microscope
  - Uses rejected starlight to measure observatory pointing jitter and telescope thermal drift
  - Close loop with a fast-steering mirror (pointing) and a deformable mirror (telescope thermal drift)
- Milestone #6 passed TAC (Technical Assessment Committee) review on 9/29/2015
  - Low order wavefront error sensing
  - Closed loop tip/tilt correction



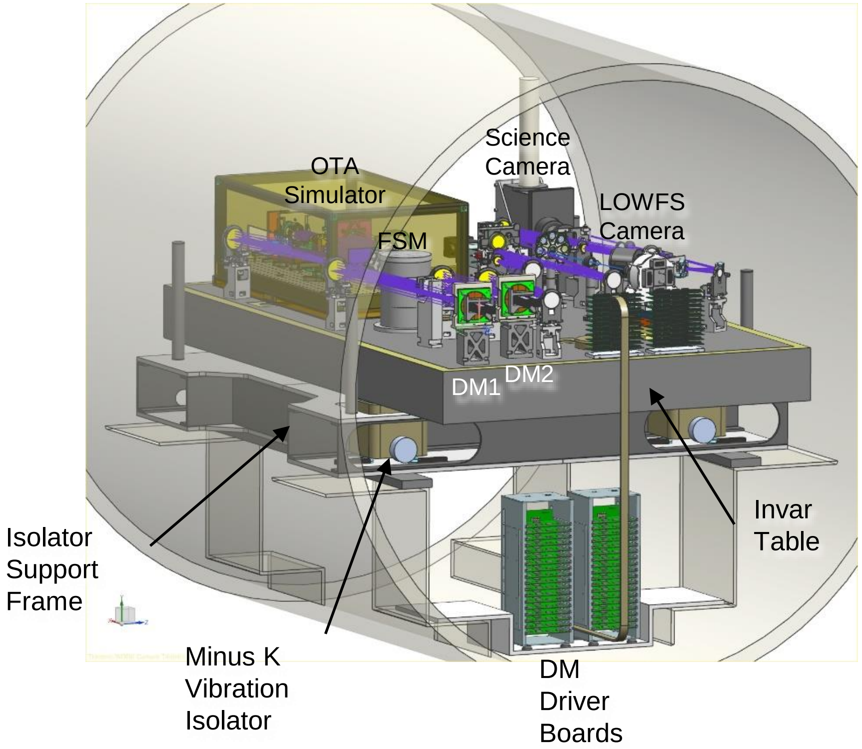


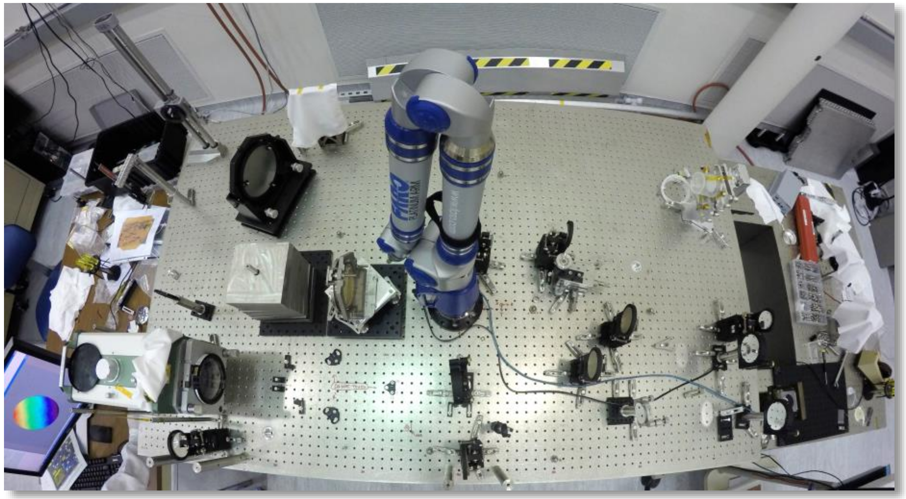
Closed loop residual LoS error ~0.3 mas rms per axis (good case), ~0.5 mas rms per axis (worst case)

Technology Advancement Plans

Hybrid Lyot & Shaped Pupil Coronagraphs

- Model validation tests
- Radiation tests of the focal plane mask
- Commission the dynamic test-bed



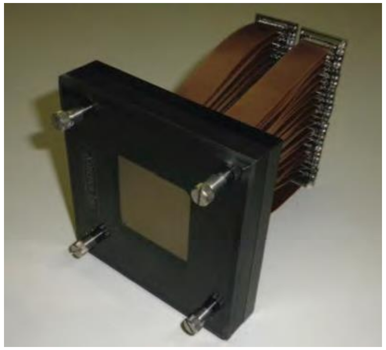


DM – Recent Progress

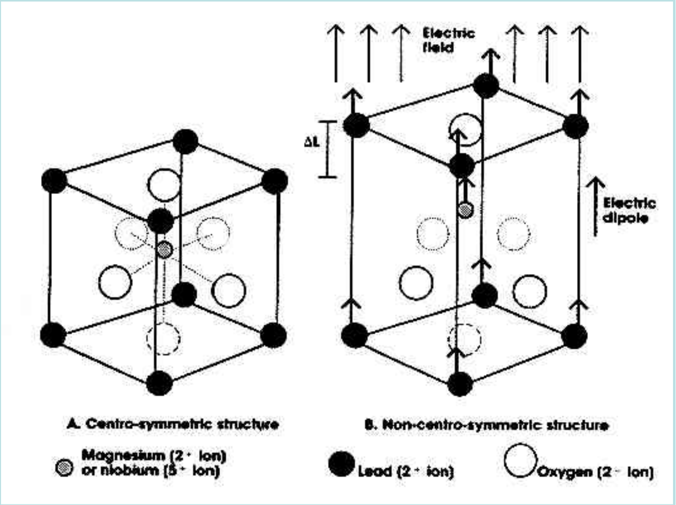
Northrop Grumman Xinetics electro-strictive Deformable Mirrors used in HCIT since 2003 (10^{-9} raw contrast demonstrated)

Recent progress
- 48×48 Interconnect design demonstrated multiple times for test-bed (vapor phase solder flow)
- New process for Photolithographic deposition of metal pads demonstrated

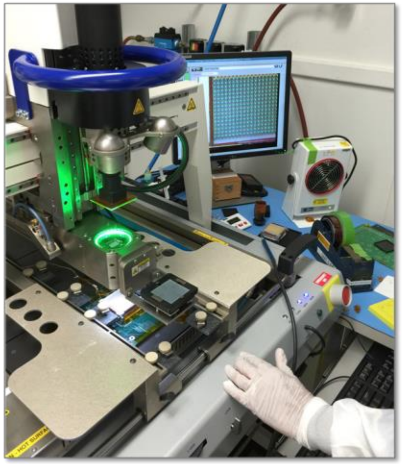
Packaged 48×48 DM, Xinetics

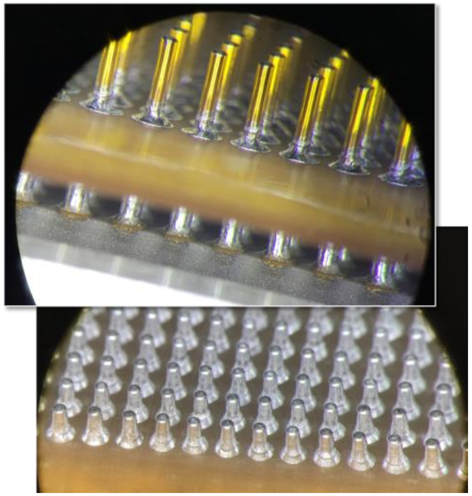


PbMgNbO Unit Cell



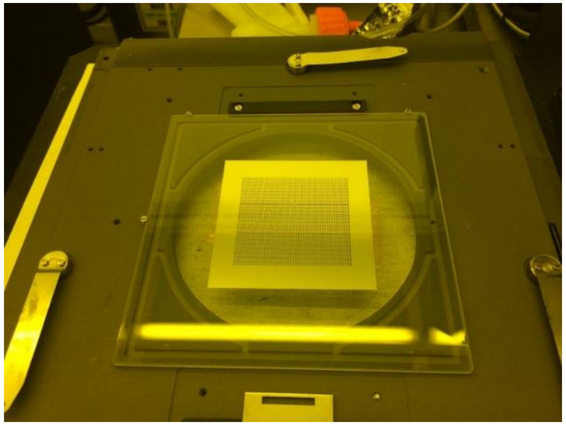
Align & Solder Attach of PGA to DM module





NORTHROP GRUMMAN

Photolithographic deposition of interconnect metal pads

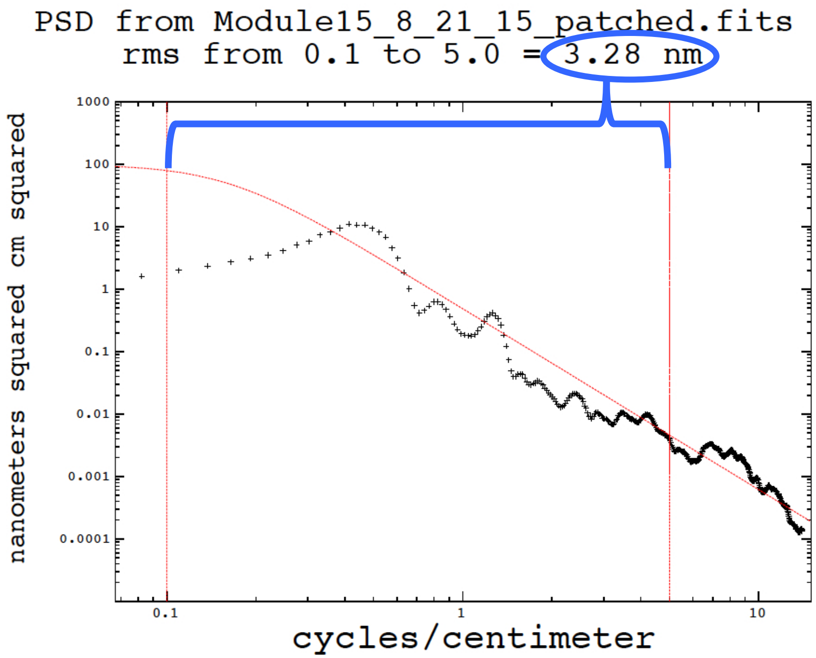


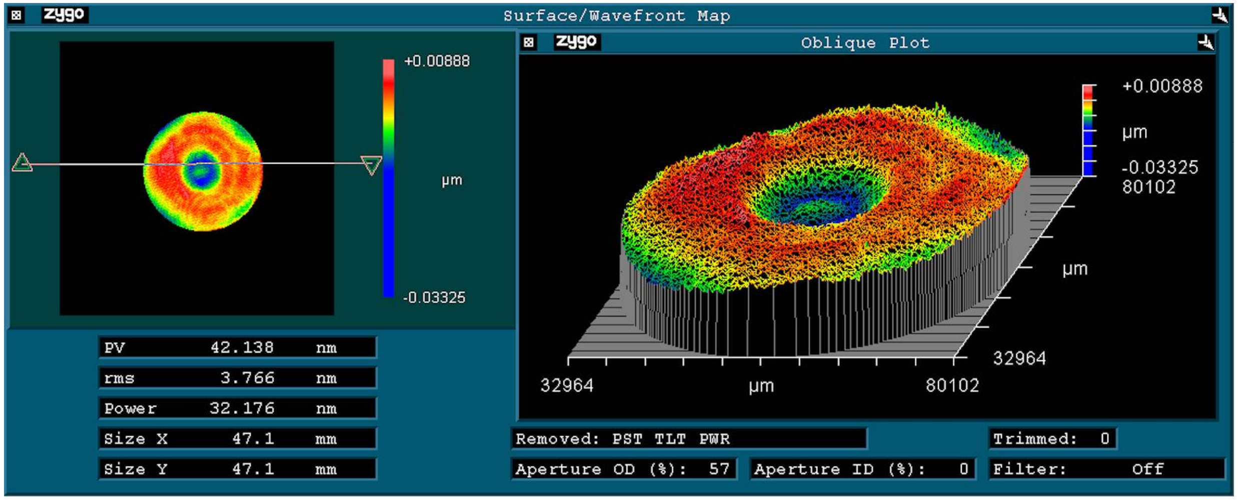
JPL

DM – Recent Progress

Most recent DM face-sheet is well within optical requirements

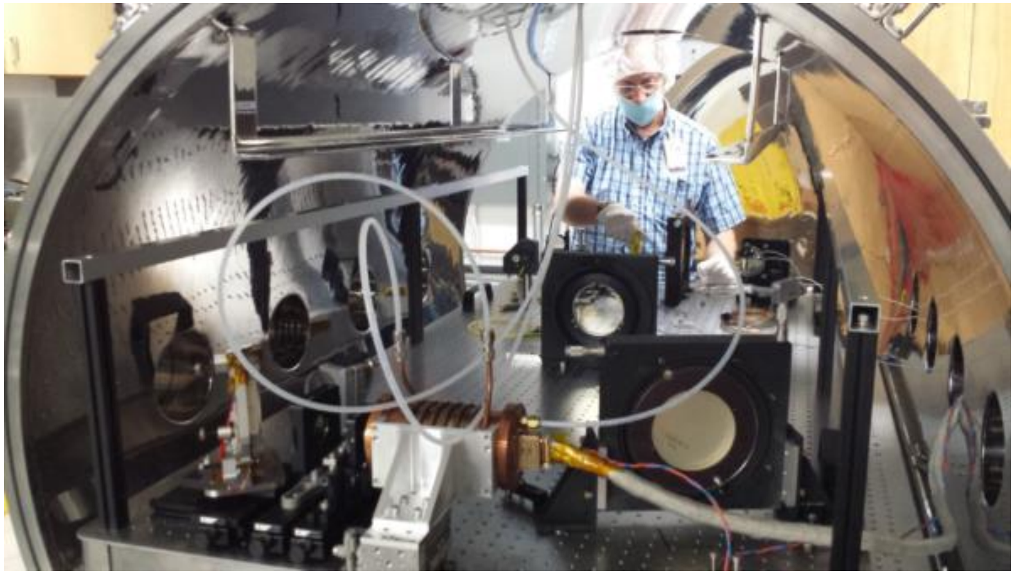
Quantity	Required	Actual
RMS surface	10 nm	3.8 nm
PV surface	100 nm	42 nm
Integrated PSD (0.1 to 5.0 cycles/cm)	3.9 nm	3.3 nm





DM – Advancement

Vacuum surface gauge for DM characterization

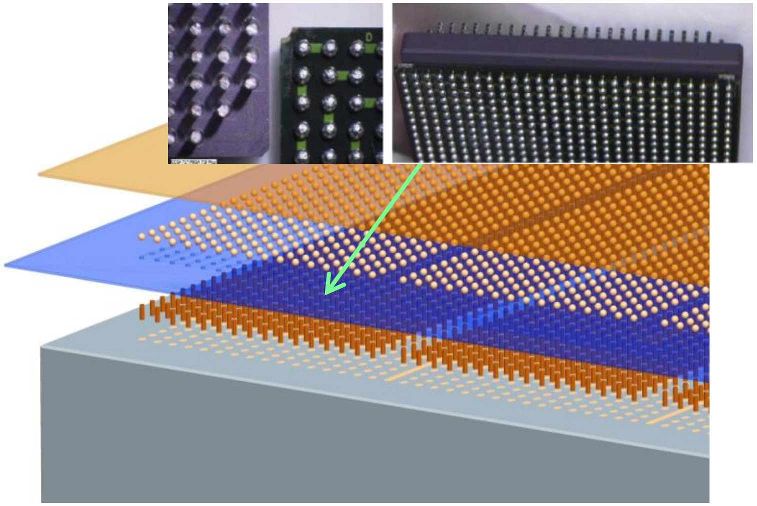


Vacuum Surface Gauge (above) in development to characterize DM actuator stroke accuracy and stability to ~30 picometers

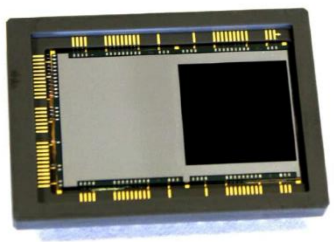
Flight Interconnect Design Study (Xinetics) has identified many design concepts

- Column Grid Array
- Pin Grid Array
- Indium bump bonds
- Fuzz Buttons

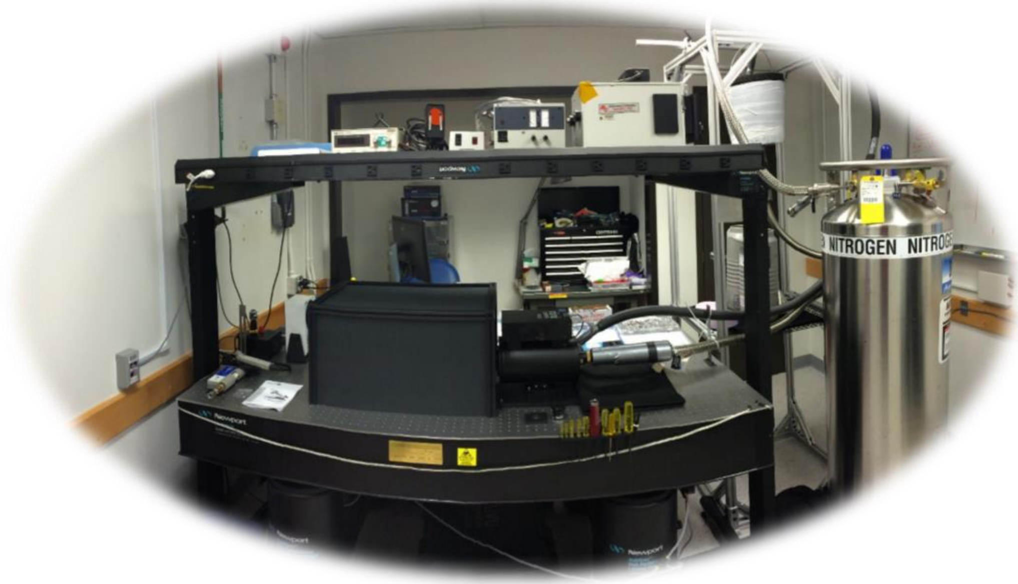
Column Grid Array based interconnect



Detector – Recent Progress



e2v CCD201-20
Electron Multiplying CCD (1K×1K format)



- E2v CCD201-20 was characterized in the WFIRST Detector lab (JPL) using a NüVü EM N2 camera
- CCD201-20 meets the WFIRST beginning of life (BOL) performance requirements

WFIRST Detector Performance Requirements

Specification	Goal	Requirement	Measurement	Unit
Effective read noise w/gain	0.2	0.2	<0.2	e^-
Dark current	1×10^{-4}	5×10^{-4}	1.01×10^{-4} *	e^-/pix/sec
Clock induced charge (CIC) @ 5.5σ threshold	0.0010	0.0018	0.0017	e^-/pix/fr

Phase I: Single Displacement Damage Dose

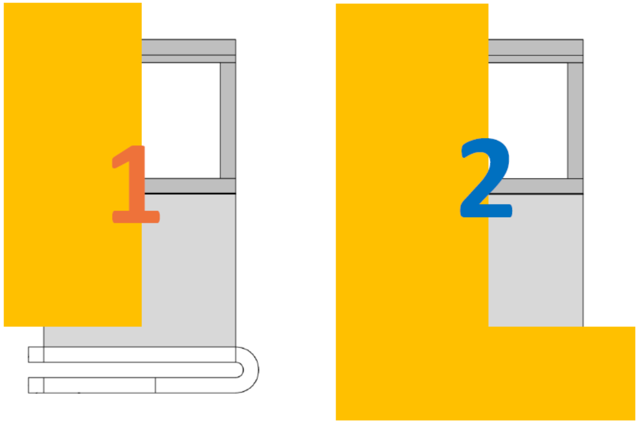
Irradiation at Paul Scherrer Institute Beamline facility in Switzerland in April 2015

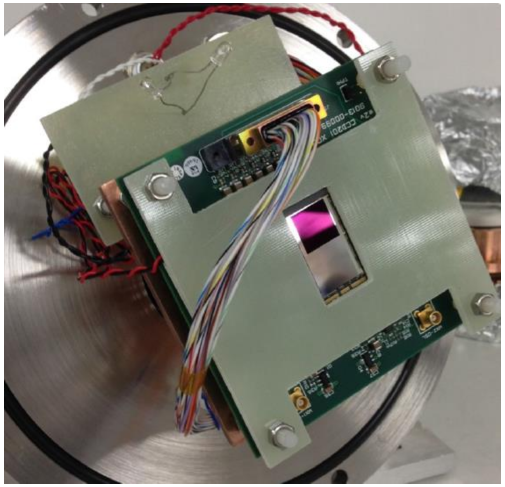
- ✓ Testing completed
- ✓ Analysis completed (final report was released in May 2015)
- Survivability test of detector for 2.5 x 10^9 protons cm^{-2} dose – 6 years at L2 orbit
  - Assumes 10 mm Ta shield
- Irradiated at room temperature
- Assessed degradation of:
  - RN, EM gain, CIC, dark current, CTE

- Devices irradiated with aluminum shielding
- Different pattern for device 1 and 2 -- used as control regions for pre-/post-analysis

Device 1: Parallel irradiation only.

Device 2: Serial and Parallel irradiation





RN = Read noise
CIC = clock induced charge
CTE = charge transfer efficiency
EM = electron multiplication

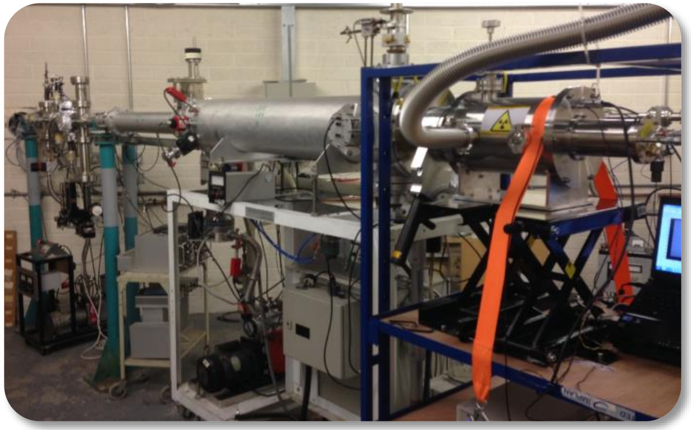
- ❖ **Detector performs well after L2 equivalent radiation**
- ❖ **Negligible change in CIC**
- ❖ **Post-irradiation Dark Current meets AFTA-C requirement**
- ❖ **Effect of degraded CTE is being assessed → will be integrated into WFIRST-C detector model**

Phase II: Cryo Displacement Damage Doses

Irradiation at Harwell Helios 3 Beamline facility in the UK in June 2015

- ✓ Testing completed
- Data analysis ongoing
- Detector maintained at T = -108 C throughout entire campaign
- Cumulative multi-dose:
  - 1 x, 2.5 x, 5.0 x, 7.5 x 10^9 protons cm^{-2}
  - Assumes <3mm Ta shield or <15mm Al
- EMCCD powered on to measure flatband voltage shifts during irradiation
- Assessed degradation of:
  - RN, EM gain, CIC, dark, CTE
  - Full characterization carried out in between each dose

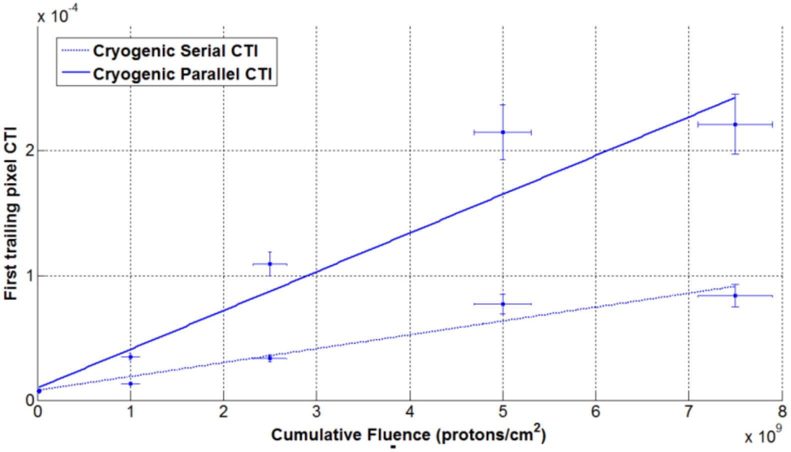
RN = Read noise
CIC = clock induced charge
CTE = charge transfer efficiency
EM = electron multiplication



Experimental setup mounted to the beamline

EPER First Deferred Pixel Results

- First Trailing Pixel CTI values show same trend of increasing CTI with Fluence.



Summary

1. Technology development phase has made considerable progress & will be completed in 2016
2. WFIRST Coronagraph DRM is advancing without driving mission complexity
3. Mass/power/cost consistent with existing flight analogs
4. Mission Concept Review in December 2015
5. Planning for a Phase A start in calendar 2016

Funded by NASA Science Mission Directorate (SMD) and Space Technology Mission Directorate (STMD).

Jet Propulsion Laboratory
California Institute of Technology

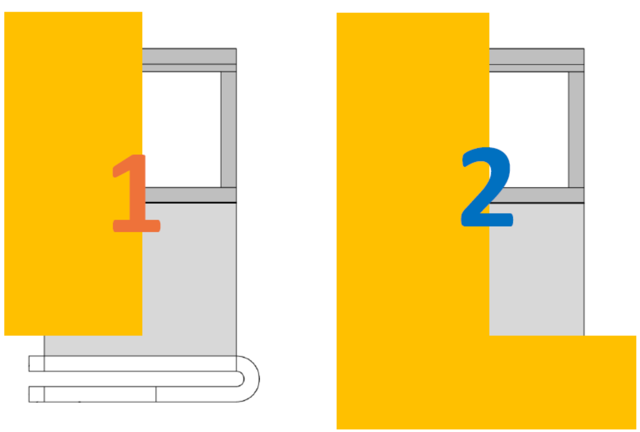
jpl.nasa.gov

Phase I: Single Displacement Damage Dose

- Devices irradiated with aluminum shielding
- Different pattern for device 1 and 2 -- used as control regions for pre-/post-analysis

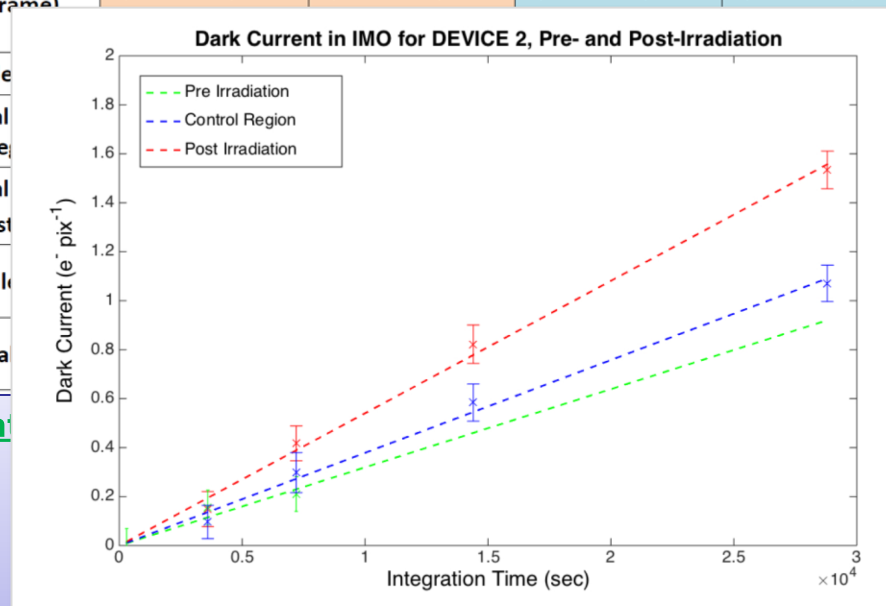
Device 1: Parallel irradiation only.

Device 2: Serial and Parallel irradiation



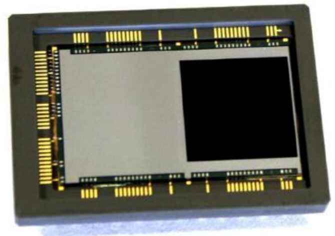
	Device 1: Parallel Irradiation only		Device 2: Irradiated in both parallel and serial direction	
Parameter	Pre-Irradiation	Post-Irradiation	Pre-Irradiation	Post-Irradiation
Multiplication gain	238±7	202±6	237±8	237±8
Parallel Dark Signal (IMO) (e^-/pix	$(7.13\pm0.49)\times10^{-5}$	$(1.22\pm0.06)\times10^{-4}$	$(3.105\pm0.50)\times10^{-5}$	$(5.75\pm0.44)\times10^{-5}$
Parallel CIC (IMO) (e^-/pixel/frame)	$(4.47\pm0.24)\times10^{-2}$	$(4.86\pm0.26)\times10^{-2}$	$(8.80\pm0.38)\times10^{-3}$	$(9.90\pm0.10)\times10^{-3}$
Fe^{55} Paralle	[illegible]	[illegible]	[illegible]	[illegible]
Fe^{55} Serial (Standard re	[illegible]	[illegible]	[illegible]	[illegible]
Fe^{55} Serial (EM regist	[illegible]	[illegible]	[illegible]	[illegible]
EPER Parall	[illegible]	[illegible]	[illegible]	[illegible]
EPER Seria	[illegible]	[illegible]	[illegible]	[illegible]

Displacement Damage Dosage (DDD) Testing
2.5×10^9 protons/cm^2
@ 10 MeV equivalent

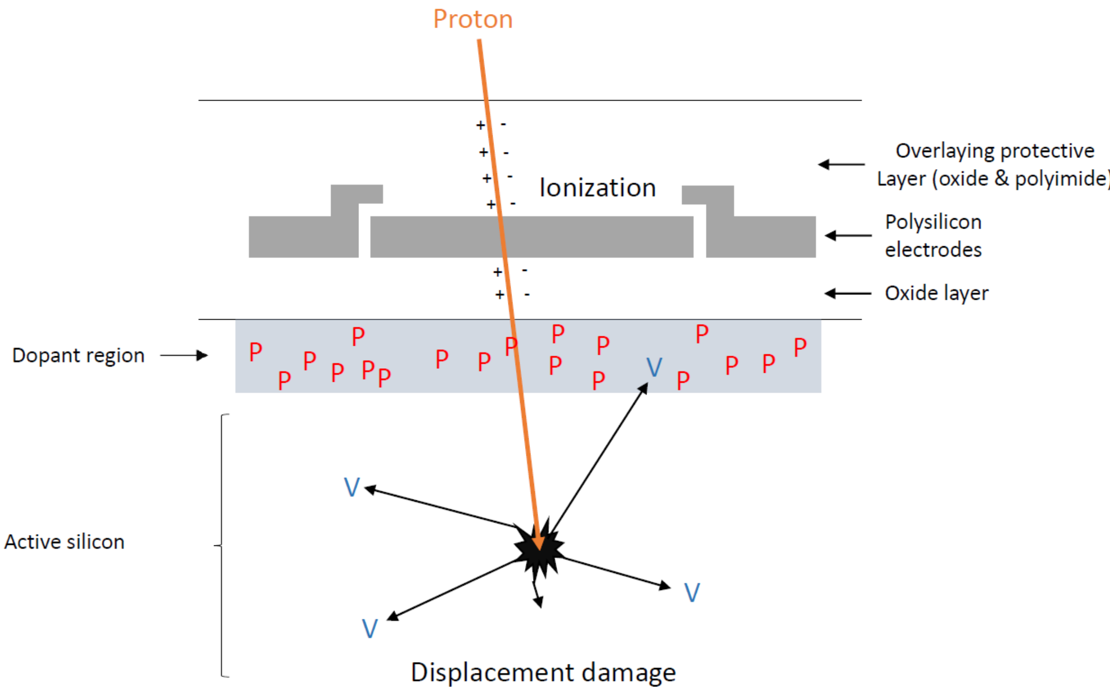


- ❖ **Detector performs well after L2 equivalent radiation**
- ❖ **Negligible change in CIC**
- ❖ **Post-irradiation Dark Current meets AFTA-C requirement**
- ❖ **Effect of degraded CTE is being assessed → will be integrated into WFIRST-C detector model**

Detector – Radiation Damage



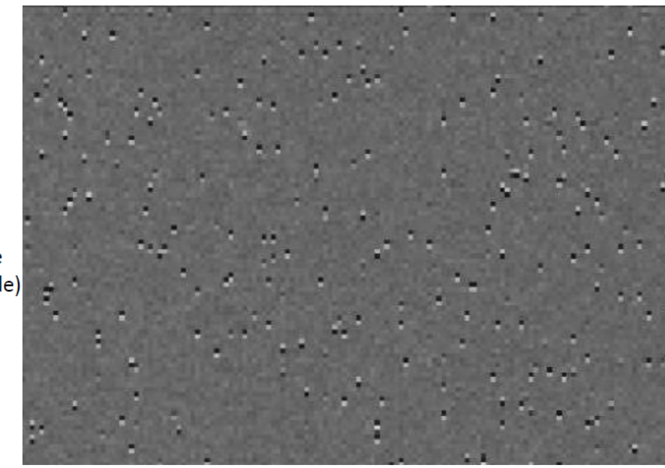
e2v CCD201-20 Electron Multiplying CCD
(1K×1K format)



P: phosphorus dopant atoms

V: vacancy diffusion

90 x 50 pixel sub-region



Trap sites

↓

Degrade CTE

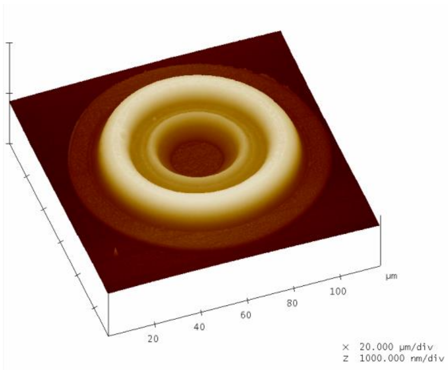
JPL

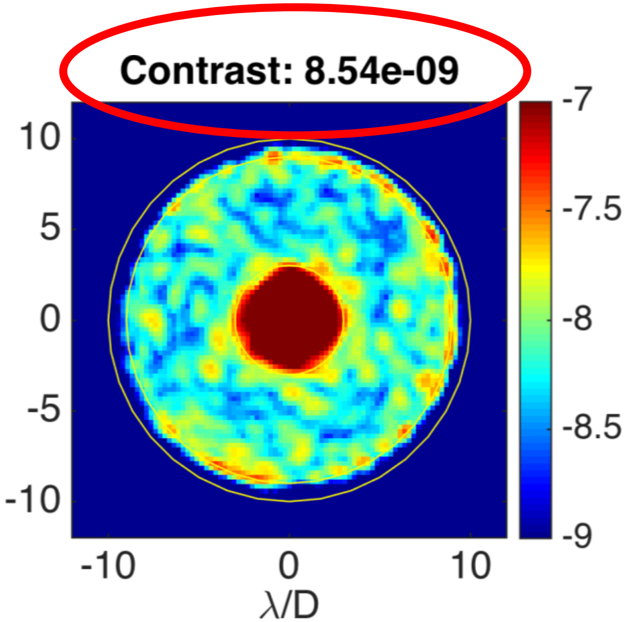
Dark Hole Contrast – Recent Progress

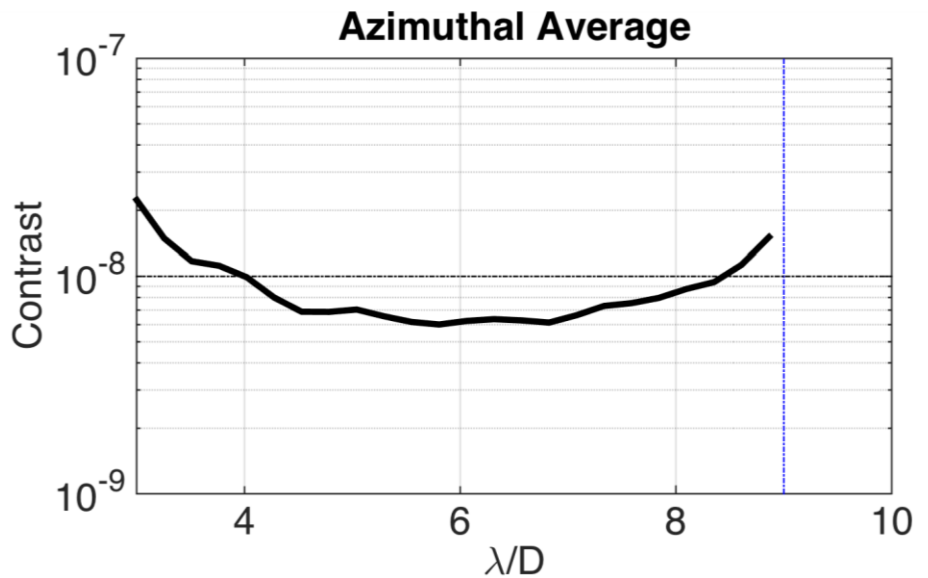
Hybrid Lyot Coronagraph

- Average contrast 8.5 x 10^{-9}
- Bandwidth 10% centered at 550nm
- Working angle: 3 - 9 λ/D
- DM stroke length greatly reduced to 170nm PV

Focal Plane Mask







Dark Hole Contrast – Recent Progress

Shaped Pupil Coronagraph

- Average contrast 8.0 x 10^{-9}
- Bandwidth 10% centered at 550nm
- Working angle: 2.8 – 8.8 λ/D
- 2-sided dark hole, 65° bow-tie

Contrast: 8.0x10^{-9}