Space Technology Mission Directorate
Game Changing Development Program
2016 Annual Program Review

National Aeronautics and
Space Administration

WFIRST Coronagraph

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WFIRST Coronagraph Instrument Manager
Jet Propulsion Laboratory
California Institute of Technology

October 19, 2016

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Government sponsorship acknowledged.

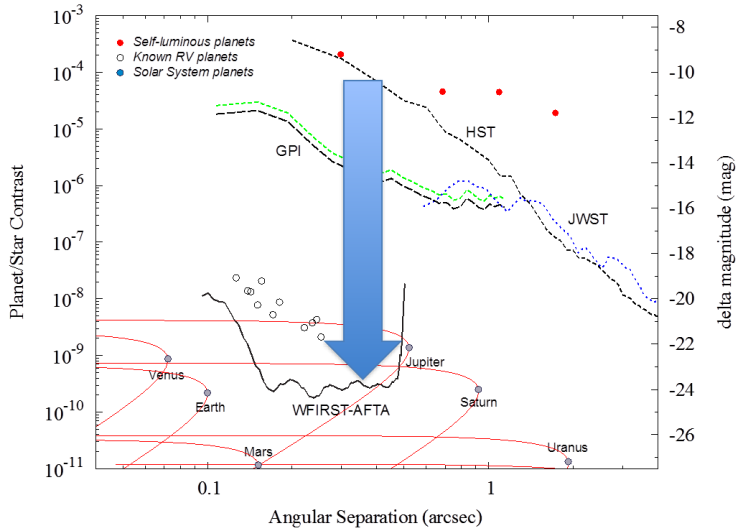
TECHNOLOGY DRIVES EXPLORATION

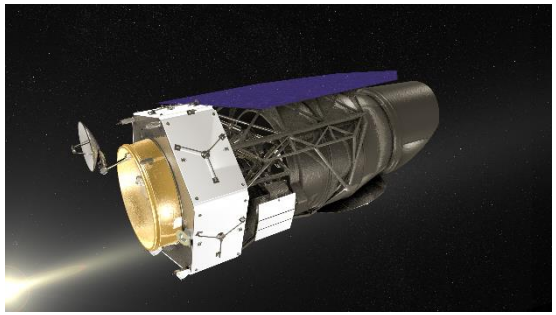
Outline

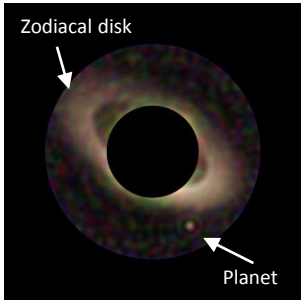
- **Overview**
- **Technical Accomplishments**
- **Resources: Obligations and Cost**
- **Economic Impact**
- **Technology Transfer - Education and Public Outreach**
- **Project Manager Assessment/Summary**
- **Back-up charts**

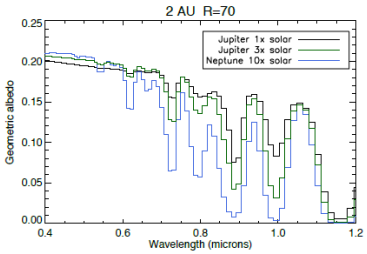
WFIRST Coronagraph Instrument (CGI)

- **Coronagraph (CGI) is the 2nd instrument on WFIRST,**
  - Exo-planet direct imaging technology demonstration
  - Pre-cursor science for future exo-earth missions
- **CGI has two science cameras:**
  - Imaging camera
  - Integral field spectral-graph (IFS)
- **CGI advances a number of new technologies:**
  - Novel coronagraph masks (shaped pupil coronagraph and hybrid Lyot coronagraph)
  - Precision wavefront sensing and control with 2 deformable mirrors (Xinetics)
  - Ultra-low noise detector



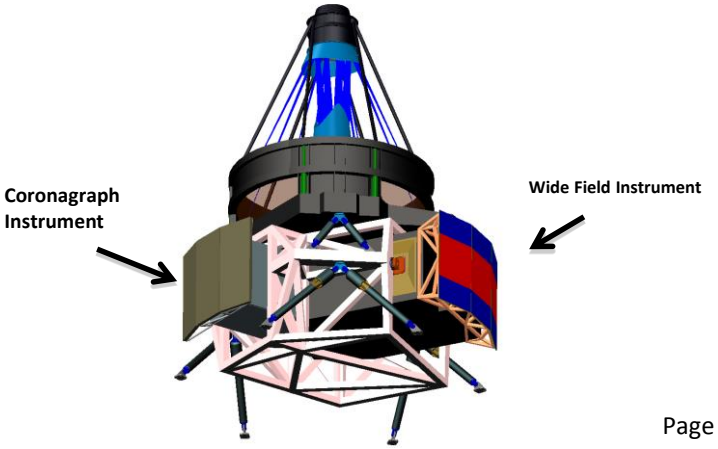






Exo-planet Direct imaging

Exo-planet Spectroscopy



WFIRST Coronagraph Overview

Integration with other projects/programs and partnerships

- Coronagraph is base-lined as part of Wide-Field Infrared Survey Telescope (WFIRST), a top-ranked space mission in the New Worlds, New Horizon (NWNH) Decadal Survey of Astronomy and Astrophysics
- Coronagraph industry partners: Northrop Grumman Xinetics
- Coronagraph academia partners: Princeton University, University of Arizona, Space Telescope Science Institute, IPAC/California Institute of Technology

Technology Infusion Plan:

- Coronagraph technology development jointly funded by SMD and STMD
- Coronagraph is baselined for WFIRST

Key Personnel:

WFIRST Project Manager: Kevin Grady, GSFC

Coronagraph Manager: Feng Zhao, JPL

Lead Center: GSFC (WFIRST); JPL (Coronagraph)

Coronagraph Supporting Centers: GSFC, ARC

NASA NPR: 7120.5

Guided or Competed: Guided

Type of Technology: Pull

Key Facts:

GCD Theme: ADSI

Execution Status: Year 3 of 4

Technology Start Date: 1/2014

Technology End Date: WFIRST Phase B

Technology TRL Start: TRL-3

Technology Current TRL: TRL-4/5

Technology Lifecycle Phase: Phase A

Coronagraph for exo-planet science

- **Also on youtube: https://www.youtube.com/watch?v=SpzeS7KBGkw**

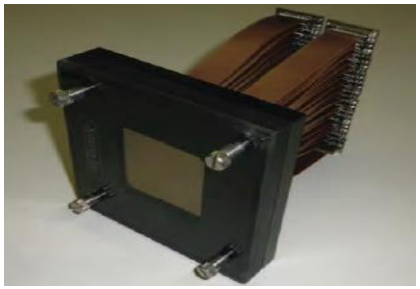
Play video here

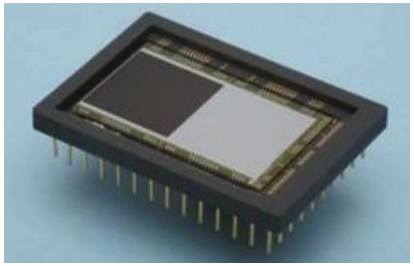
Key Coronagraph Technologies

- **Contrast → Star light suppression**
  1. Coronagraphic masks (diffraction)
  2. Deformable mirrors (scattered light)

- **Contrast Stability → Wavefront Control**
  3. Low-Order Wavefront Sensing & Control (pointing jitter and thermal changes)

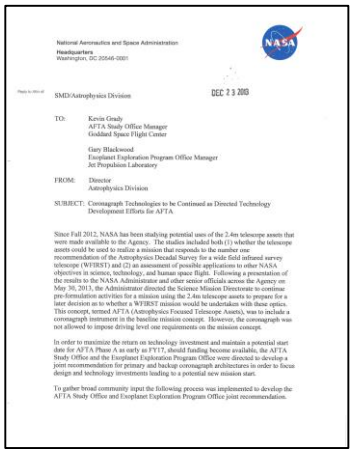
- **Detection Sensitivity**
  4. Ultra-low noise visible detectors





WFIRST Coronagraph Technology Plan

- **December 2013 , NASA selected two coronagraph architectures for WFIRST:**
  - OMC (Occulting Mask Coronagraph) as the primary architecture
    - Combines shaped pupil and Hybrid Lyot coronagraphs
    - Lower technical risk
  - PIAACMC (Phase Induced Amplitude Apodization Complex Mask Coronagraph) as the backup architecture
    - Higher technical risk, with potential higher science yield
  - ACWG recommendation and Paul Hertz direction Memo can be found from:
    - http://wfirst.gsfc.nasa.gov/science/AFTA_Coronagraph_Arch_Selection/HQ_Dir_FY14_Coronagraph_Tech_Invest_Dec23_2013.pdf
- **December 2013, SMD (Paul Hertz) and STMD (James Reuther) signed MOU on joint investment on WFIRST coronagraph technology development**
- **March 2014, Technology Development Plan was approved by APD, with nine milestones tracking the development of WFIRST coronagraph technology**
- **Coronagraph technology team have made remarkable progress, demonstrated appropriate technology readiness levels to the WFIRST mission**



National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

DEC 23 2013

SMD/Astrophysics Division

TO: Kevin Grady
AFTA Study Office Manager
Goddard Space Flight Center

Gary Blackwood
Exoplanet Exploration Program Office Manager
Jet Propulsion Laboratory

FROM: Director
Astrophysics Division

SUBJECT: Coronagraph Technologies to be Continued as Directed Technology Development Efforts for AFTA

Since Fall 2012, NASA has been studying potential uses of the 2.4m telescope assets that were made available to the Agency. The studies included both (1) whether the telescope assets could be used to realize a mission that responds to the number one recommendation of the Astrophysics Decadal Survey for a wide field infrared survey telescope (WFIRST) and (2) an assessment of possible applications to other NASA objectives in science, technology, and human space flight. Following a presentation of the results to the NASA Administrator and other senior officials across the Agency on May 30, 2013, the Administrator directed the Science Mission Directorate to continue pre-formulation activities for a mission using the 2.4m telescope assets to prepare for a later decision as to whether a WFIRST mission would be undertaken with these optics. This concept, termed AFTA (Astrophysics Focused Telescope Assets), was to include a coronagraph instrument in the baseline mission concept. However, the coronagraph was not allowed to impose driving level one requirements on the mission concept.

In order to maximize the return on technology investment and maintain a potential start date for AFTA Phase A as early as FY17, should funding become available, the AFTA Study Office and the Exoplanet Exploration Program Office were directed to develop a joint recommendation for primary and backup coronagraph architectures in order to focus design and technology investments leading to a potential new mission start.

To gather broad community input the following process was implemented to develop the AFTA Study Office and Exoplanet Exploration Program Office joint recommendation.

WFIRST-AFTA Coronagraph Technology Development Plan
JPL D-81964, Initial Release: March 17, 2014
Page 1

JPL Document D-81964

WFIRST Wide-Field Infrared Survey Telescope

WFIRST-AFTA Coronagraph Instrument

Technology Development Plan

Preliminary Release

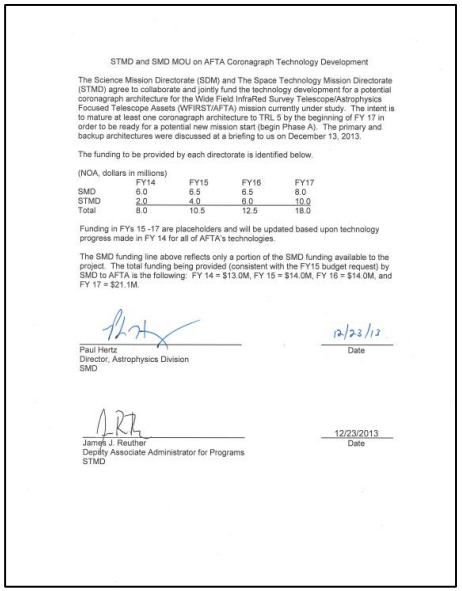
Paper copies of this document may not be current and should not be relied on for official information. The current version is in the JPL PDMS Repository at the following URL: https://pdms.jpl.nasa.gov

Document Owner: Ilya Poberezhskiy

Released by:

March 17, 2014

JPL Jet Propulsion Laboratory California Institute of Technology



STMD and SMD MOU on AFTA Coronagraph Technology Development

The Science Mission Directorate (SDM) and The Space Technology Mission Directorate (STMD) agree to collaborate and jointly fund the technology development for a potential coronagraph architecture for the Wide Field InfraRed Survey Telescope/Astrophysics Focused Telescope Assets (WFIRST/AFTA) mission currently under study. The intent is to mature at least one coronagraph architecture to TRL 5 by the beginning of FY 17 in order to be ready for a potential new mission start (begin Phase A). The primary and backup architectures were discussed at a briefing to us on December 13, 2013.

The funding to be provided by each directorate is identified below.

(NOA, dollars in millions)

	FY14	FY15	FY16	FY17
SMD	6.0	6.5	6.5	8.0
STMD	2.0	4.0	6.0	10.0
Total	8.0	10.5	12.5	18.0

Funding in FYs 15 -17 are placeholders and will be updated based upon technology progress made in FY 14 for all of AFTA's technologies.

The SMD funding line above reflects only a portion of the SMD funding available to the project. The total funding being provided (consistent with the FY15 budget request) by SMD to AFTA is the following: FY 14 = $13.0M, FY 15 = $14.0M, FY 16 = $14.0M, and FY 17 = $21.1M.

Paul Hertz
Director, Astrophysics Division
SMD

12/23/13
Date

James J. Reuther
Deputy Associate Administrator for Programs
STMD

12/23/2013
Date

Coronagraph 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

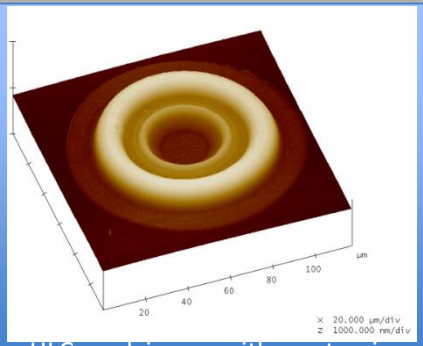
✓ Reviewed and approved by Technical Assessment Committee

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

Key Enabling Technology: coronagraph masks and occulters

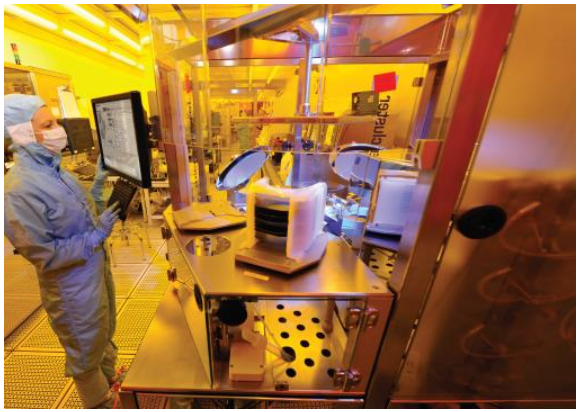
- **Pupil plane and focal plane masks/occulters are a key enabling technology for starlight suppression**
- **Design: Mask design is a collaboration among multiple institutions:**
  - **Shaped pupil coronagraph (SPC) mask: Kasdin group, Princeton University**
  - **Hybrid Lyot Coronagraph (HLC) mask: Trauger group, JPL**
- **Fabrication: Masks fabricated and characterized at JPL's Micro Devices Lab:**
  - **SPC mask: black silicon**
  - **HLC masks: nano fabrication**
- **Environmental testing: Recently completed radiation test with HLC mask and no observable signs of degradation**

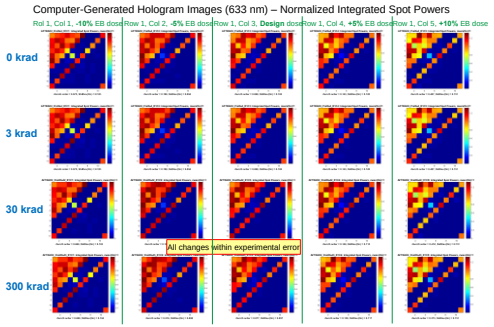
SPC mask image with an optical microscope



HLC mask image with an atomic force microscope

Mask fabrication with E-beam facility at JPL's Micro Devices Laboratory (MDL)



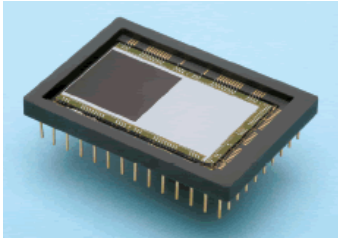


- Tested PMGI (HLC mask dielectric) to ~200x mission dose (Co-60)
  - No noticeable change in optical properties

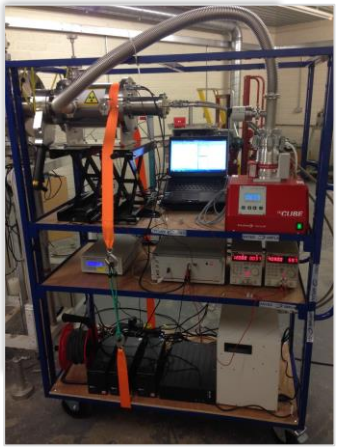
Technology Milestone #7 -- Low Noise Detector

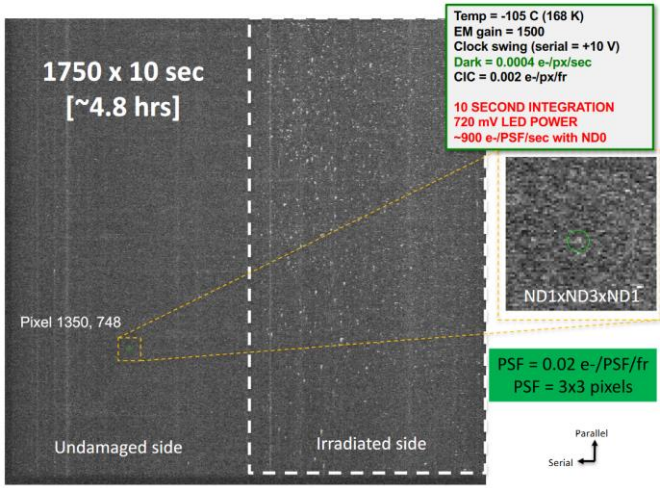
- e2v Electron Multiplying CCD (EMCCD) is base-lined for WFIRST Coronagraph
- Performance at beginning of life (BOL) meets requirements. Technology development focuses on environmental effects (radiation) and mitigations

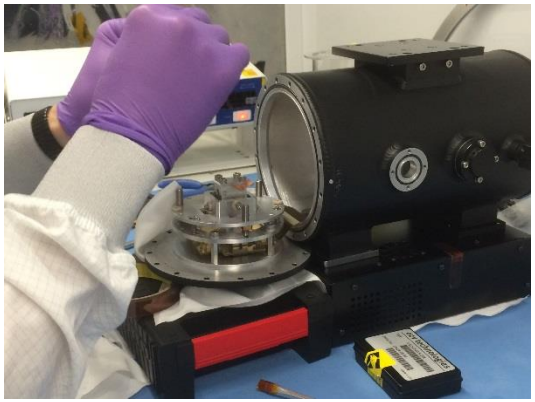
- **Radiation tests**
  - Test report of cryo-radiation testing campaign completed
    - Conventional CCD performance parameters nearly pass EOL requirements, easily mitigated by beefier shielding design
    - Irradiation at room temperature for unbiased operation resulted in lower performance degradation than at cryogenic temperature under bias at an equivalent exposure
    - Effects of room temperature anneal are favorable for dark current and low flux CTI
- **Both lab testing and modeling results presented to the Technical Assessment Committee (TAC).**
- **TAC reviewed the results and concurred that Milestone #7 passed! (9/19/2016)**



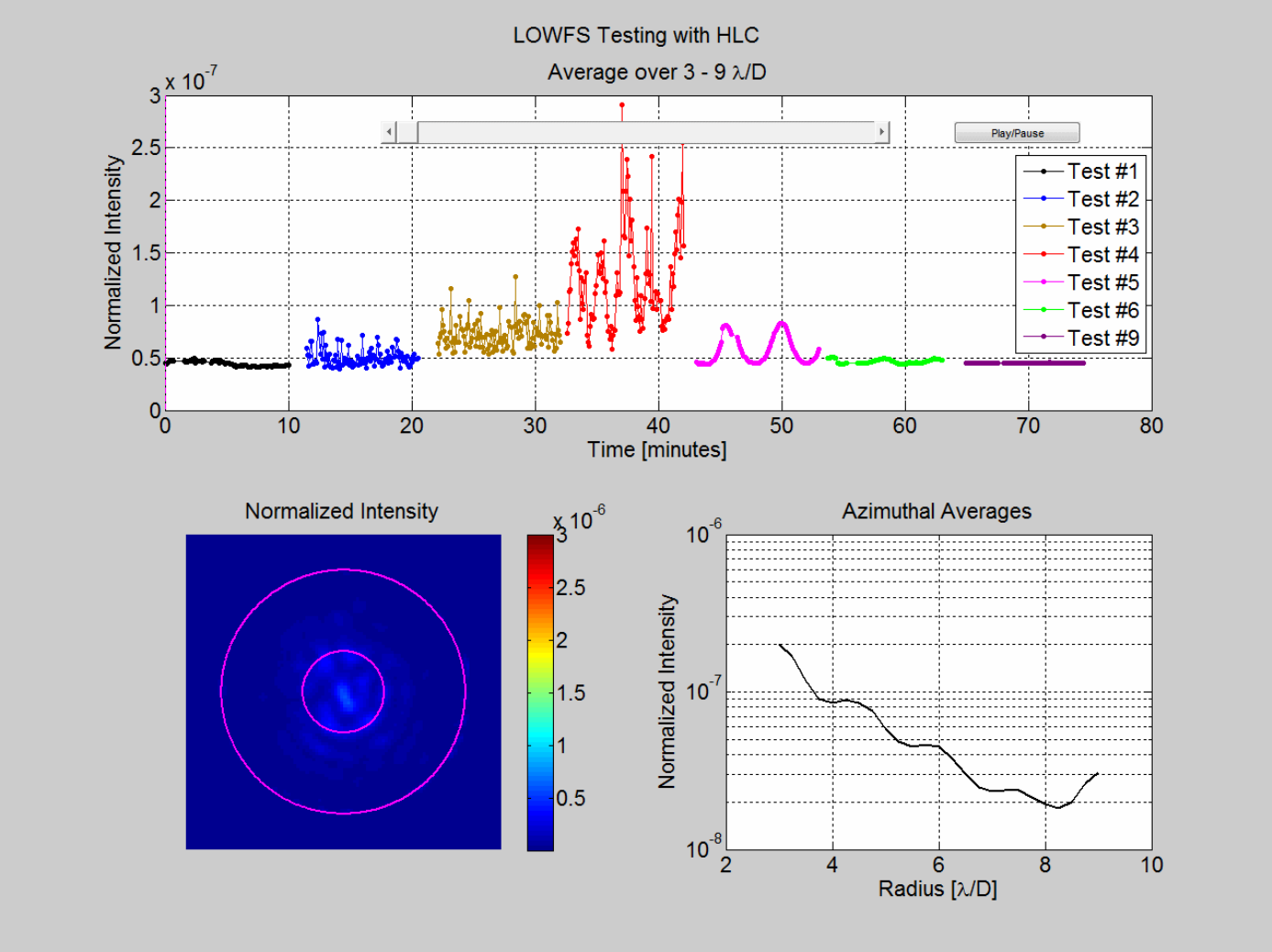
e2v CCD201-20
Electron Multiplying CCD
(1K×1K format)







Technology Milestone #9 – OMC Dynamics Testbed



Submitted Milestone 9 Report

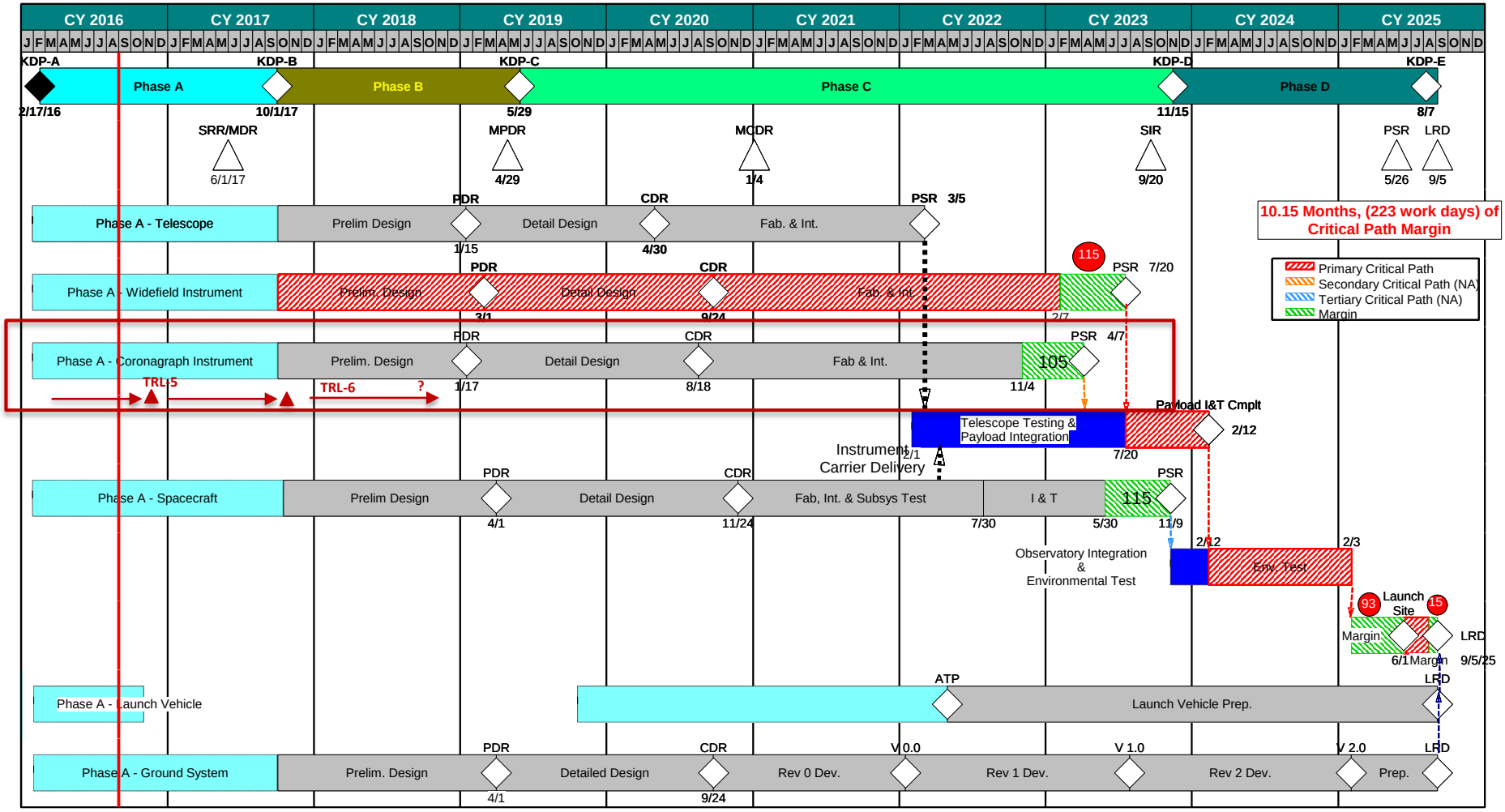
Aspect of Milestone 9	Status	Comments
Coronagraph works with tip/tilt loop closed	Done	Pointing error suppression demonstrated in HLC mode.
Coronagraph works with LOWFE loop closed using DM	Done	Low order wavefront control demonstrated with deformable mirror
Broadband 10% dark hole < 10^{-8}	Broadband HLC <u>modulated</u> light <10^{-8} <u>Unmodulated</u> light ~$2x10^{-8}$ 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).

Technology Milestone #8 – PIAA-CMC Testbed

- **Back-up coronagraph technology: Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAA-CMC)**
- **Current results:**
  - **Monochromatic contrast ~ 5×10^{-8}**
    - **Dominated by incoherent light**
  - **Broadband contrast ~ 10^{-6}**
    - **Preliminary**
    - **Limited by time, not fundamentals**
  - **Have not reached the goal of 1×10^{-8}**
- **Milestones 1 through Milestone 9 clearly confirm that current OMC architecture is more mature, represents a lower risk to WFIRST mission.**
- **Recommendation:**
  - Continue OMC as the baseline architecture for WFIRST coronagraph
    - Descope and backup options exist within OMC architecture
  - Wrap up PIAACMC testbed and document PIAA results in a white paper (per TDEM), and return the PIAA effort to ExEPO to support future technology and mission studies

WFIRST Development Schedule (2025 Launch)

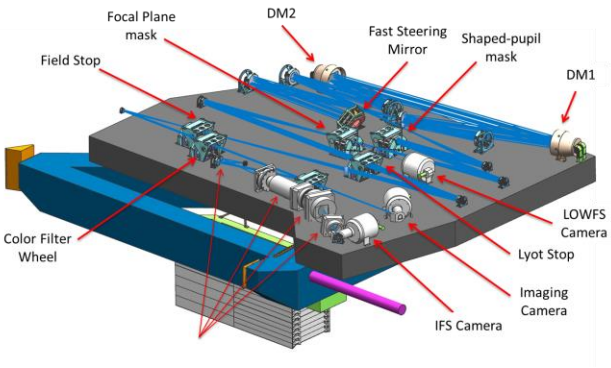
Preliminary WFIRST Development Schedule
(Grassroots Planning)

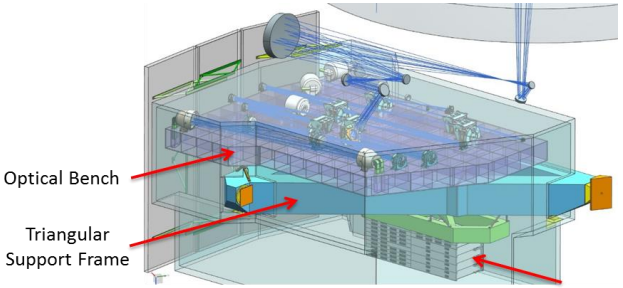


Grass-root Phase B/C/D schedule under development. Technology maturation to be aligned with Project Gates

Coronagraph is Baselined for WFIRST

- **Successfully passed WFIRST Mission Concept Review (MCR), 12/8-10/2015**
- **Successfully completed WFIRST KDP-A, 2/17/2016**
- **Completed ASM. Coronagraph assigned to JPL, 8/2016**
- **December 2015, NASA announced selection of:**
  - Coronagraph Adjutant Scientist (CAS): Jeremy Kasdin, Princeton University
  - Science Investigations Teams (SIT):
    - SIT #1 PI: Bruce Macintosh, Stanford University
    - SIT #2 PI: Maggie Turnbull, SETI Institute

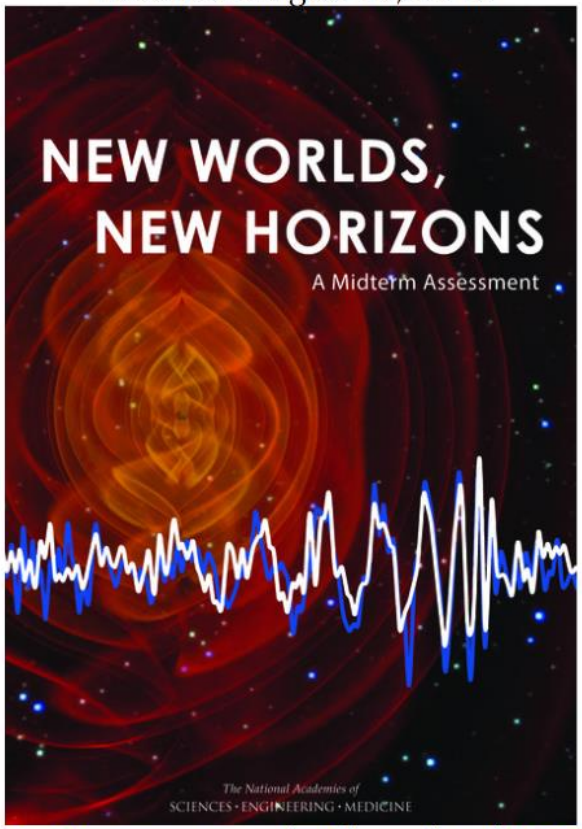




NRC Midterm Assessment

- National Research Council (NRC) completed mid-decadal assessment, report released August 15, 2016
- "At the currently estimated cost, NASA's decision to add a coronagraph to WFIRST is justifiable within the scientific goals of NWNH. The broader societal interest in the possibility of life beyond Earth is also compelling. However, an increase in cost much beyond the currently estimated $350 million would significantly distort the science priorities set forth by NWNH." (Finding 4-4)

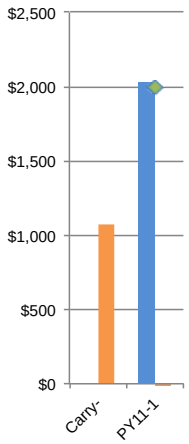
Released August 15, 2016

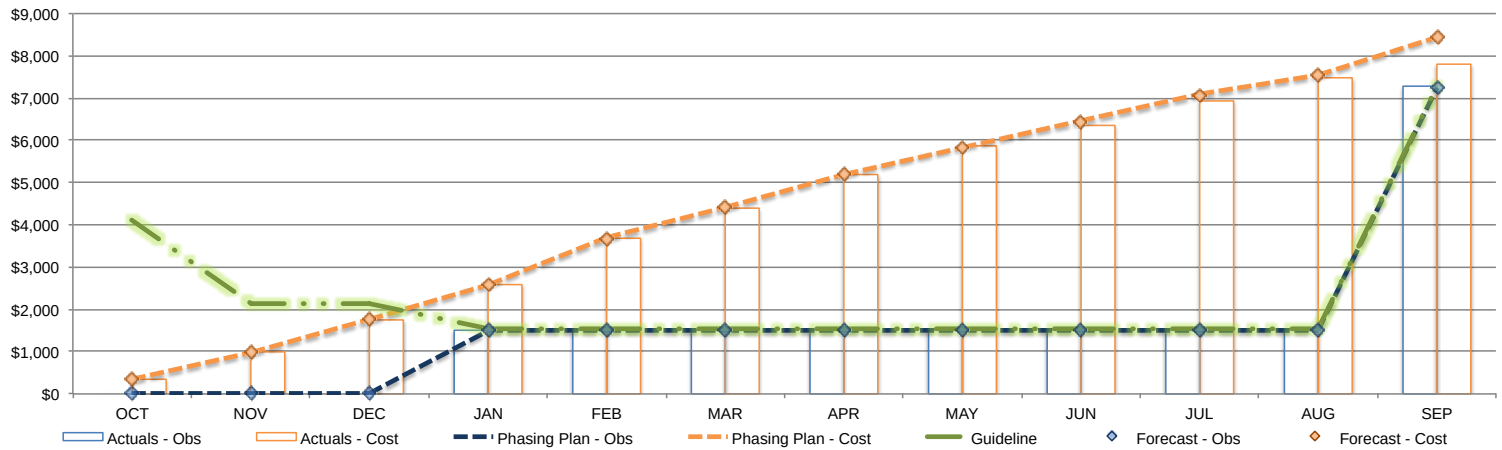


http://www.nap.edu/download/23560

Resources: Total Obligations and Cost

FY 2016 Non-Labor Financial Status





	Cum ($K)	Carry-In	PY11-15 Funds	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Carry Out
	Guideline		2,000.0	4,126.1	2,126.1	2,126.1	1,533.3	1,533.3	1,533.3	1,533.3	1,533.3	1,533.3	1,533.3	1,533.3	7,283.3	
Obs	Phasing Plan (RLP)			0.0	0.0	0.0	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	7,256.9	0.0
Obs	Actuals	0.0	2,026.4	0.0	0.0	0.0	1,506.9	1,506.9	1,506.9	1,521.3	1,521.3	1,521.3	1,521.3	1,533.3	7,283.3	0.0
Obs	Forecast			-	-	-	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	1,506.9	7,256.9	0.0
Cost	Phasing Plan (RLP)			346.0	992.4	1,758.8	2,599.8	3,695.4	4,409.8	5,203.2	5,847.7	6,452.2	7,079.9	7,540.0	8,445.8	5,146.2
Cost	Actuals	1,075.1	(3,207.3)	346.0	995.7	1,751.3	2,587.6	3,683.3	4,397.6	5,191.0	5,870.4	6,354.1	6,932.8	7,481.1	7,803.7	(520.4)
Cost	Forecast			346.0	995.7	1,751.3	2,587.6	3,683.3	4,397.6	5,191.0	5,835.5	6,440.0	7,067.8	7,527.8	8,433.7	5,158.4

Note: Carry-In is the unobligated/uncosted portion of PY11-15 funding end of FY15

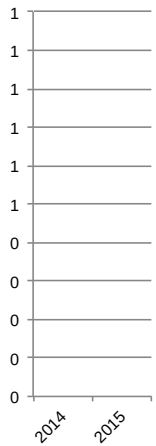
	YTD Status			Explanation required for YTD Variance in excess of 5% from Phasing Plan (shaded red)
'16 Obs	Phasing	$	7,257	
'16 Obs	Forecast*	$	7,257	
'16 Obs	Actuals	$	7,283	
'16 Obs	Variance	$	26	
'16 Cost	Phasing	$	8,446	Variance due to workforce unavailability as well as delayed funds obligation to Xinetics in support of the CGI Technology Deformable Mirror.
'16 Cost	Forecast*	$	8,434	
'16 Cost	Actuals	$	7,804	
'16 Cost	Variance	$	(642)	

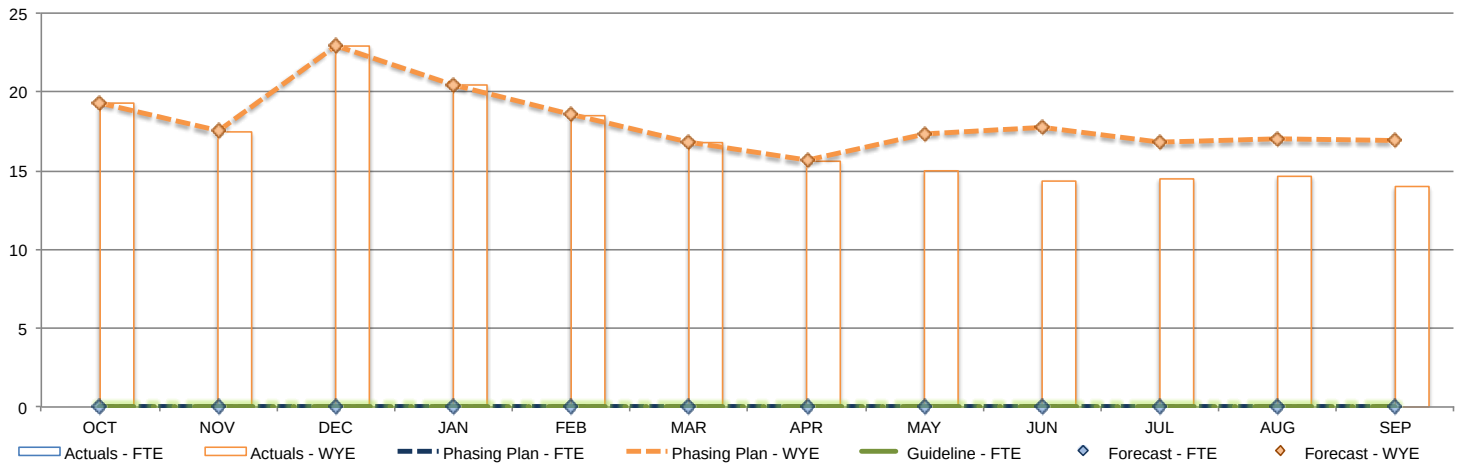
* Forecast value is a snapshot of the Forecast from the previous reporting period

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech

Resources: Total Project Workforce

FY 2016 Workforce Status





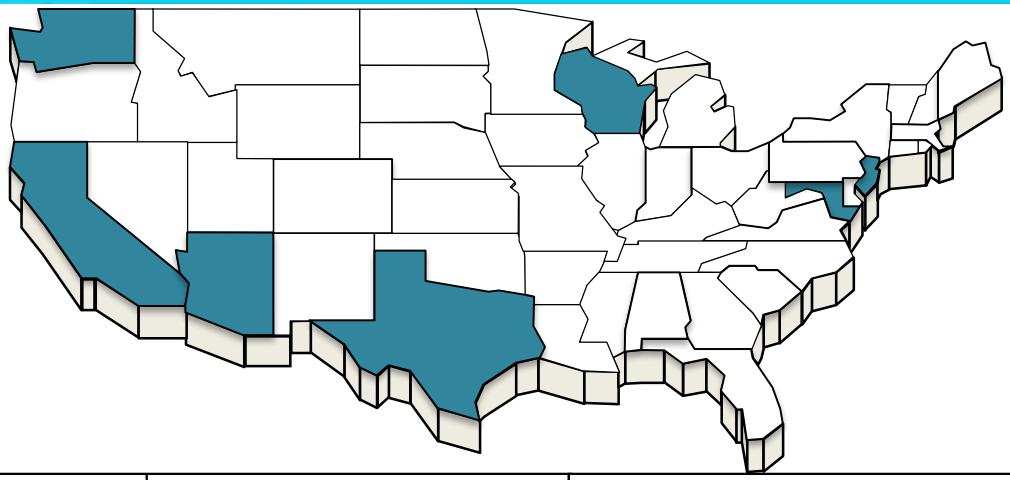
	Incremental	2014	2015	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	2016 Avg
FTE	Guideline				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FTE	Phasing Plan (RLP)															0.0
FTE	Actuals	0	0													
FTE	Forecast															
WYE	Phasing Plan (RLP)			19.3	17.5	23.0	20.4	18.6	16.8	15.6	17.4	17.8	16.8	17.0	16.9	18.1
WYE	Actuals	0.0	0.0	19.3	17.5	22.9	20.4	18.5	16.8	15.6	15.0	14.3	14.5	14.6	14.0	17.0
WYE	Forecast			19.3	17.5	23.0	20.4	18.6	16.8	15.6	17.4	17.8	16.8	17.0	16.9	18.1

	YTD Status		Explanation required for YTD Variance in excess of 5% from Phasing Plan (shaded red)
'16 FTE	Phasing	N/A	
	Forecast*	N/A	
	Actuals	N/A	
	Variance	N/A	
'16 WYE	Phasing	18.1	Underrun not significant. Mainly due to workforce unavailability.
	Forecast*	18.1	
	Actuals	17.0	
	Variance	(1.1)	

* Forecast value is a snapshot of the Forecast from the previous reporting period

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech

Economic Impact



= Above $10M

= Between $9.99M and $5M

= Between $4.99M and $1M

= Between $0.99M and $0.01M

= $0M

Program Year	Vendor Name (Who is building the Technology)	Where is the Work being Completed? (Where work is being performed)		Program Year Obs ($M)
PY16	ADAPTIVE OPTICS ASSOCIATES INC	Devens	MA	0.48
PY16	CALTECH	Pasadena	CA	0.28
PY16	FIRST LIGHT IMAGING	San Francisco	CA	0.03
PY16	NKT PHOTONICS INC	Birkerod	Denmark	0.01
PY16	PI PHYSIK INSTRUMENTE LP	Irvine	CA	0.01
PY16	PRINCETON UNIVERSITY	Princeton	NJ	0.37
PY16	SPACE TELESCOPE SCIENCE INSTIT	Baltimore	MD	0.23
PY16	THE OPEN UNIVERSITY	Buckinghamshire	UK	0.14
PY16	UNIVERSITY OF ARIZONA	Tucson	AZ	0.22
PY16	NU-TEK PRECISION OPTICAL CORP	Aberdeen	MD	0.04
PY16	ZEMAX LLC	Kirkland	WA	0.02
PY16	DELL MARKETING LP	Round Rock	TX	0.03
PY16	PHOTON ENGINEERING LLC	Tucson	AZ	0.02
PY16	MADE CITY LABS INC	Madison	WI	0.01
PY16	SILICON ARTIST INC	Irvine	CA	0.06

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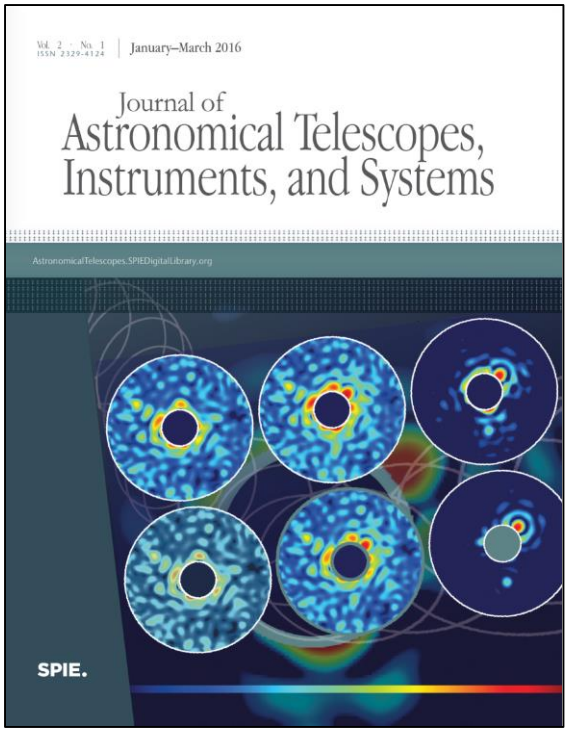
Publications and Conferences

- **Journal of Astronomical Telescopes, Instruments, and Systems, <u>Special Edition</u> on WFIRST Coronagraph**
  - 22 peer-reviewed papers
  - Strong interest from both technical and science communities
- **WFIRST Coronagraph Sessions during the SPIE Astronomical Telescopes + Instrumentation Conference (2016, Edinburg)**



TUESDAY 28 JUNE

SESSION 9
LOCATION: SHERATON – EDINBURGH SUITE 1 . . . .TUE 10:30 TO 12:10

WFIRST I

Session Chair: **Nicholas Siegler,** Jet Propulsion Lab. (USA)

10:30: **Wide-Field InfraRed Survey Telescope (WFIRST) slitless spectrometer: design, prototype, and status**, Qian Gong, NASA Goddard Space Flight Ctr. (USA) . . . . . [9904-32]

10:50: **Canadian contributions study for the WFIRST coronagraph instrument**, Jean-Francois Lavigne, ABB Analytical Measurement (Canada) . . . . . [9904-33]

11:10: **The WFIRST coronagraph instrument: from technology advancement to flight design**, Richard T. Demers, Jet Propulsion Lab. (USA) . . . . . [9904-34]

11:30: **WFIRST-AFTA coronagraph starlight suppression technology progress**, Ilya Y. Poberezhskiy, Jet Propulsion Lab. (USA) . . . . . [9904-35]

11:50: **Exoplanet and disk detection with the WFIRST coronagraph**, Wesley A. Traub, Jet Propulsion Lab. (USA) . . . . . [9904-36]

Lunch/Exhibition Break . . . . . .Tue 12:10 to 13:40

SESSION 10
LOCATION: SHERATON – EDINBURGH SUITE 1 . . . TUE 13:40 TO 15:00

WFIRST II

Session Chair: **Gary W. Matthews,** Exelis Geospatioal Systems (USA)

13:40: **Managing the optical wavefront for high contrast exoplanet imaging with the WFIRST-AFTA coronagraph**, John T. Trauger, Jet Propulsion Lab. (USA) . . . . . [9904-37]

14:00: **Low-order wavefront sensing and control for WFIRST coronagraph**, Fang Shi, Jet Propulsion Lab. (USA) . . . . . [9904-38]

14:20: **Closing the contrast gap between testbed and model prediction with WFIRST-AFTA shaped pupil coronagraph**, Hanying Zhou, Jet Propulsion Lab. (USA) . . . . . [9904-39]

14:40: **PISCES: The WFIRST coronagraph integral field spectrograph technology demonstrator**, Michael W. McElwain, NASA Goddard Space Flight Ctr. (USA). . . . . [9904-119]

Coffee Break . . . . . .Tue 15:00 to 15:30

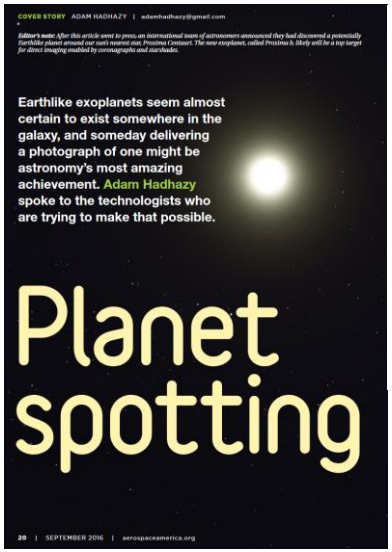
Public Outreach

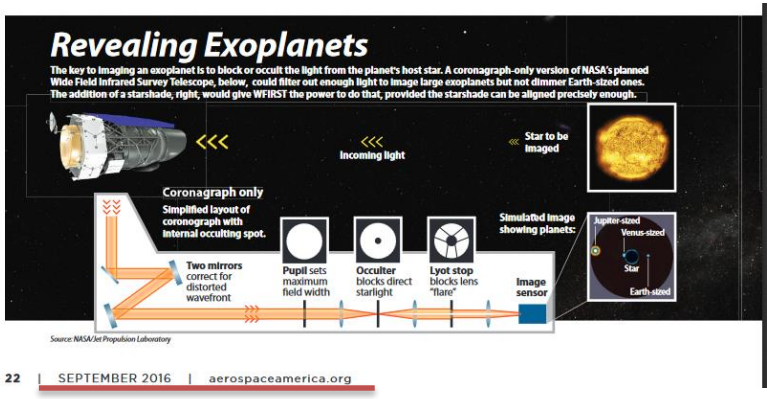
Global News Connect

WFIRST-AFTA: GROUNDBREAKING SPACE OBSERVATORY TO IMAGE EXOPLANETS AND TACKLE A UNIVERSE OF QUESTIONS

IN OCTOBER 21, 2015 BY ADMIN LEAVE A COMMENT

http://globalnewsconnect.com/wfirst-afta-groundbreaking-space-observatory-to-image-exoplanets-and-tackle-a-universe-of-questions/





JPL Open House

http://www.aerospaceamerica.org/Documents/Aerospace_America_PDFs_2016/September2016/CoverStory_PlanetSpotting_EditorsNote_AASept2016.pdf

Project Manager Assessment/Summary

Project Element / Subtask	Performance	TRL Assessment			Major Deliverables/ Comments
		Planned	Start	Finish	
WFIRST Coronagraph	T C S	TRL4	TRL 3	TRL5/6	Major FY 16 deliverables: Technology Milestones #7 review completed and passed! Milestone #8 and #9 review scheduled for November 8

T = Technical, C = Cost, S = Schedule

Plans for FY2017

- **Systems Requirement Review (SRR) and Mission Definition Review (MDR)**
  - WFIRST mission, June 2017
  - Coronagraph Instrument, July 2017
- **Key KDP-B Gate Products, including Phase B/C/D/E cost estimate**
- **Key "technology" activities:**
  - OMC Testbed:
    - Same optical prescription as the flight instrument design (cycle #6)
    - Address science observation scenario questions under "critical environments" such as "low-flux", "convergent rate", etc.
  - Deformable mirror:
    - Continue engineering development units, both module production, and flight interconnect development. Driver electronics development
  - Low-noise detector:
    - Continue pushing low flux measurement capability, investigate CCD201 chip modifications to enhance performance, readout electronics development

Coronagraph Development Summary

- **Team is making good progress on coronagraph technology maturation to achieve appropriate TRL by WFIRST Phase A**
- **Flight coronagraph instrument design is advanced and detailed, not driving mission complexity**
- **WFIRST coronagraph addresses key 2010 NWNH technology and science goals**
  - WFIRST coronagraph brings wavefront-controlled coronagraphy to flight levels on the path to future Earth finding missions, not just hardware, but algorithms
  - 2016 Mid-Decadal review strongly endorses addition of coronagraph to WFIRST mission
- **Currently in Phase A, preparing SRR/MDR and major gate products such as Phase B/C/D schedule and cost**
  - Stay within the cost constraints
  - FY17 plan folds into over-all WFIRST development

National Aeronautics and
Space Administration

Backup chart

WFIRST Coronagraph Overview

Integration with other projects/programs and partnerships

- Coronagraph is base-lined as part of Wide-Field Infrared Survey Telescope (WFIRST), a top-ranked space mission in the New Worlds, New Horizon (NWNH) Decadal Survey of Astronomy and Astrophysics
- Coronagraph industry partners: Northrop Grumman Xinetics
- Coronagraph academia partners: Princeton University, University of Arizona, Space Telescope Science Institute, IPAC/California Institute of Technology

Technology Infusion Plan:

- Coronagraph technology development jointly funded by SMD and STMD
- Coronagraph is baselined for WFIRST

Key Personnel:

WFIRST Project Manager: Kevin Grady, GSFC

Coronagraph Manager: Feng Zhao, JPL

Lead Center: GSFC (WFIRST); JPL (Coronagraph)

Coronagraph Supporting Centers: GSFC, ARC

NASA NPR: 7120.5

Guided or Competed: Guided

Type of Technology: Pull

Key Facts:

GCD Theme: ADSI

Execution Status: Year 3 of 4

Technology Start Date: 1/2014

Technology End Date: WFIRST Phase B

Technology TRL Start: TRL-3

Technology Current TRL: TRL-4/5

Technology Lifecycle Phase: Phase A

WFIRST Coronagraph Key Members

- WFIRST is managed by GSFC
  - WFIRST project manager: Kevin Grady
  - WFIRST Project Scientist: Neil Gehrels
- Coronagraph instrument is managed by JPL
  - JPL WFIRST Project Acting Manager: Ben Parvin (7060)
  - JPL WFIRST Project Scientist: Wes Traub (3200)
  - Instrument Manager: Feng Zhao (3830)
  - Deputy Instrument Manager: Rick Demers (383D)
  - Instrument Systems Engineer: Ilya Poberezhskiy (383H)
- Other coronagraph partner institutions:
  - NASA centers:
    - GSFC (responsible for integral field spectrograph)
    - ARC (supporting backup technology PIAA-CMC)
  - Industry:
    - Northrup Grumman Xinetics (deformable mirror)
    - e2v (Electron Multiplying CCD – EMCCD)
  - Science Investigations Teams (SIT):
    - SIT #1 PI: Bruce Macintosh, Stanford University
    - SIT #2 PI: Maggie Turnbull, SETI Institute
  - Coronagraph Adjutant Scientist (CAS):
    - Jeremy Kasdin, Princeton University
  - Science Center:
    - IPAC/Caltech, STScI
  - Potential International Partners:
    - Germany -- Max Planck Institute of Astronomy (mask filter wheels)
    - UK/ESA – e2v (EMCCD)
    - Japan – JAXA (polarization module)

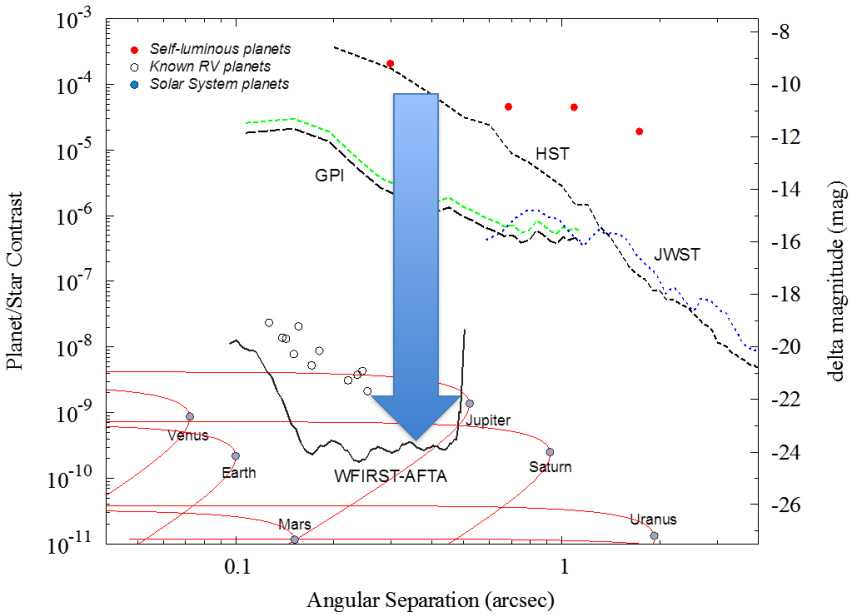
The Problem – The Solution

The Problem

- **Direct imaging of exoplanets allows their spectral characterization, revealing their atmospheric composition and, potentially, signs of life**
- **WFIRST/AFTA mission concept includes the first high-contrast coronagraph in space**
  - **Space coronagraph technology's TRL needs to be increased**
  - **Previous work on high-contrast coronagraph development was focused on unobscured telescope pupils, WFIRST/AFTA pupil is obscured**

The Solution

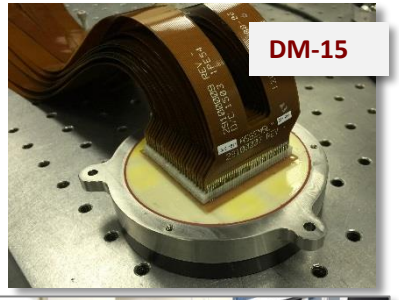
- **Novel shaped pupil, hybrid Lyot coronagraph designs invented to work with AFTA telescope pupil geometry (as well as jitter, thermal drift, etc) and produce high contrast at small working angles**
- **Developed a plan to mature WFIRST/AFTA coronagraph technology to TRL5 by 9/2016**
  - **9 milestones in FY 2014 – 2016**
  - **Independent Technology Assessment Committee (TAC)**
  - **Demonstrate coronagraph starlight suppression performance in presence of optical wavefront disturbances expected on orbit**
  - **Mature key components – spectrograph detector and deformable mirror – to TRL6**

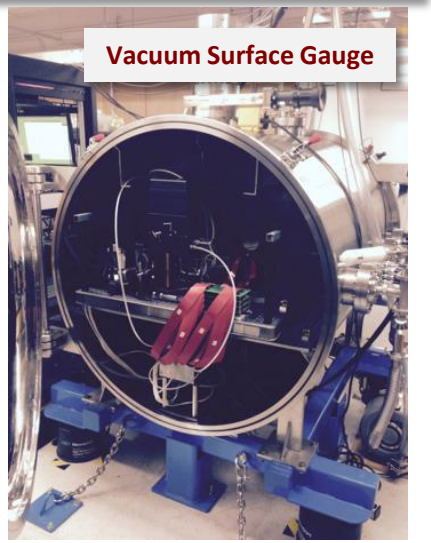


- **Coronagraph tech demo will produce new science; validate technology for exo-Earth mission**
- **WFIRST/AFTA coronagraph contrast exceeds existing instruments by 3+ orders of magnitude**
  - **Can see different, more interesting planets, such as exo-Jupiters and Neptunes, and possibly super-Earths**

Technology -- Deformable Mirror

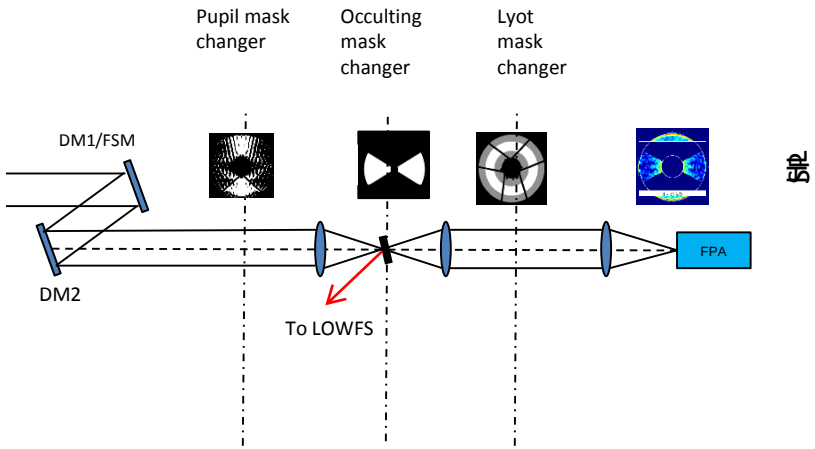
- **Test-bed DMs:**
  - Received all testbed DMs
  - Two of them went through testing under picometer class Vacuum Surface Gauge, and now are being used in the HCIT testbeds
  - Third DM is being use for flight calibration requirement development
- **Flight Interconnect Development**
  - Design concept study was completed
  - ROM was received for prototyping of two leading design concepts
  - Contract Ts & Cs are being negotiated
- **New Module Pilot Production**
  - First fabrication block completed and inspections underway
  - Longer stroke DM module design in hand as risk mitigation for CGI contrast budget
    - Modified module design for ~25% longer stroke completed as part of this contract
    - Manufacturing tooling for longer-stroke modules will be fabricated as part of this contract
  - Fabrication of second and third blocks to be started in FY17 under a new contract



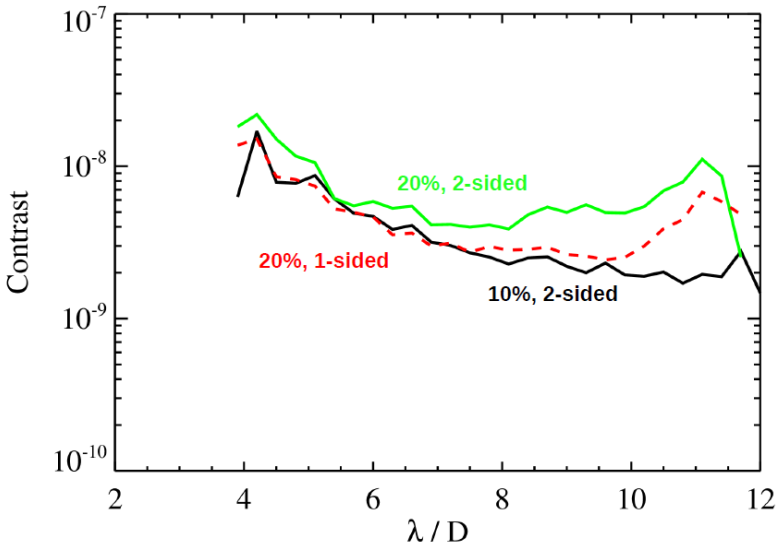


Coronagraph Architecture

- Primary coronagraph architecture: Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot
- SP and HL share same optical layout
- Operate with different apodizing and occulting masks
- In “HL mode,” the OMC affords the potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for most of the reaction wheel speeds
- In “SP mode,” the OMC provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk.



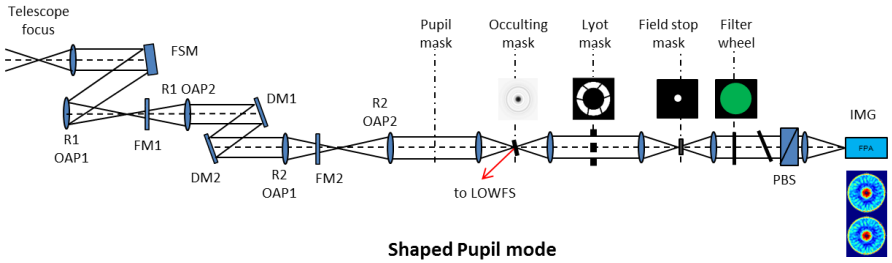
Shaped Pupil, Post-EFC



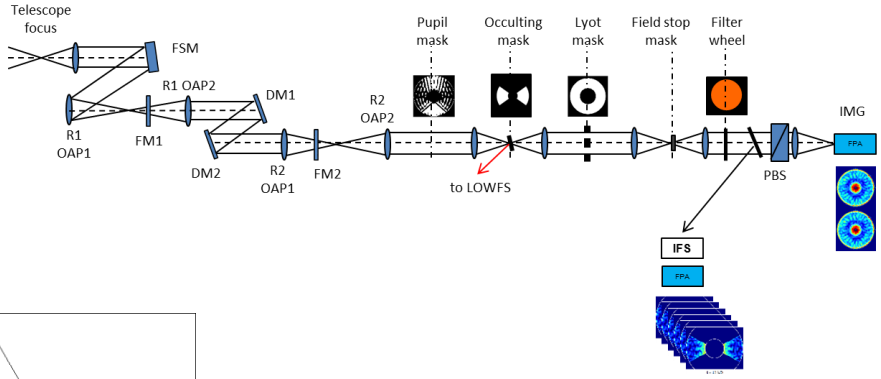
Primary Architecture – Occulting Mask Coronagraph (OMC)

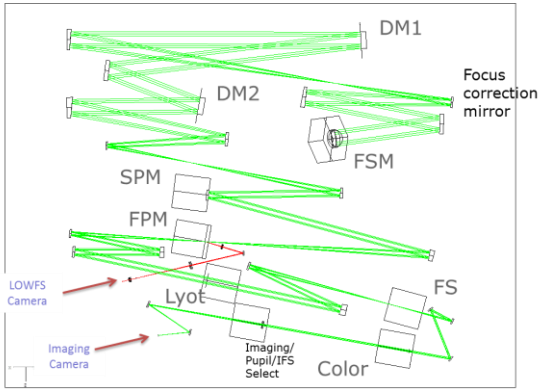
- **Primary coronagraph architecture was chosen in 2013 by AFTA Coronagraph Working Group (ACWG)**
  - Hybrid Lyot Coronagraph (HLC) mode
  - Shaped-pupil Coronagraph (SPC) mode
- **Coronagraph DRM flight design evolves due to flight bench orientation, volume constraints, etc., by using different number of fold mirrors**
- **TRL-6 coronagraph testbed optical layout builds on same OMC architecture and with same prescription (48X48DM, shaped-pupil mask, occulting masks, Lyot stops, field-of-view, pixel scale, optical coatings, etc.) on a bread-board optical bench that can be modeled for performance validation**

Hybrid Lyot mode

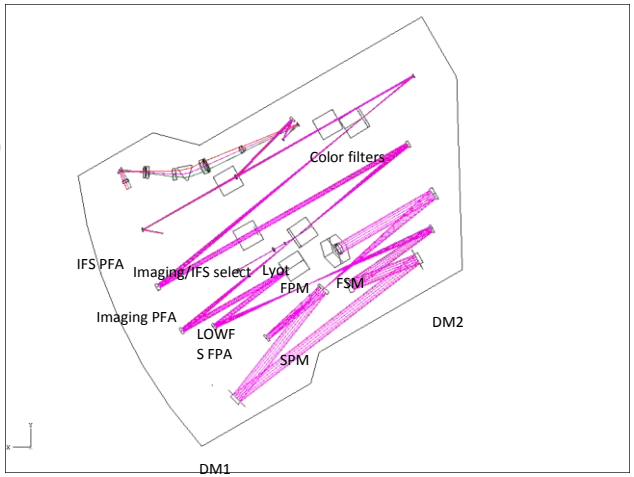


Shaped Pupil mode

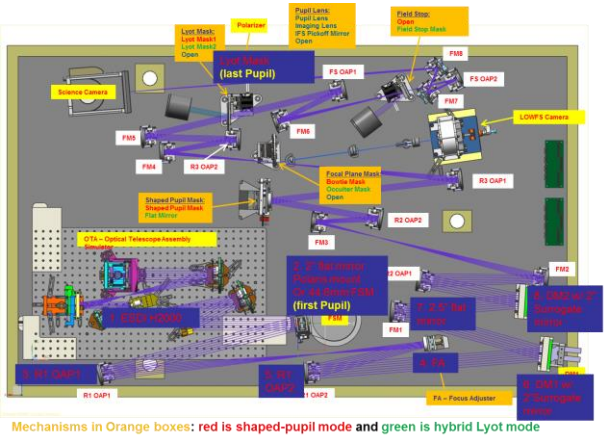




DRM Cycle #5 CGI Design (2014)



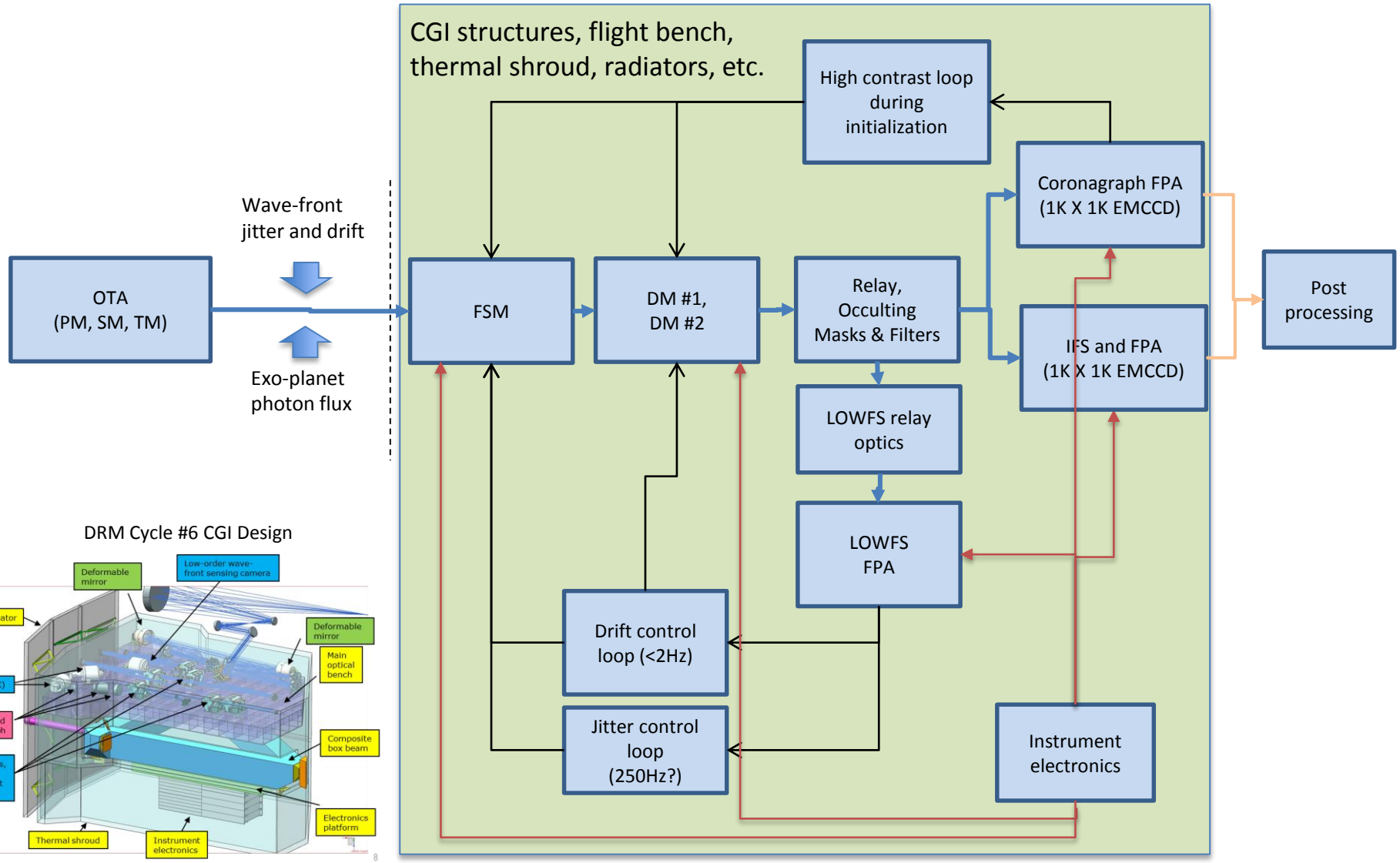
DRM Cycle #6 CGI Design (2015)



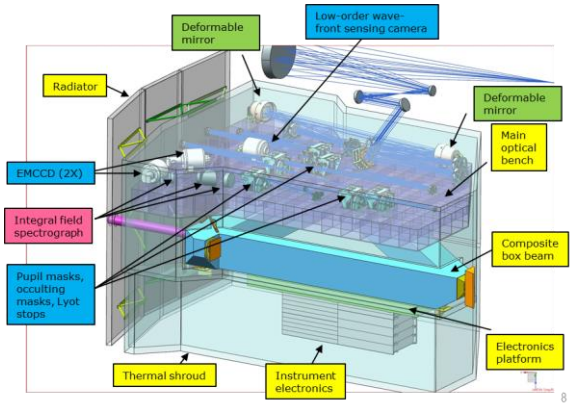
Mechanisms in Orange boxes: red is shaped-pupil mode and green is hybrid Lyot mode

Coronagraph systems testbed (ver. O, May 7, 2015)

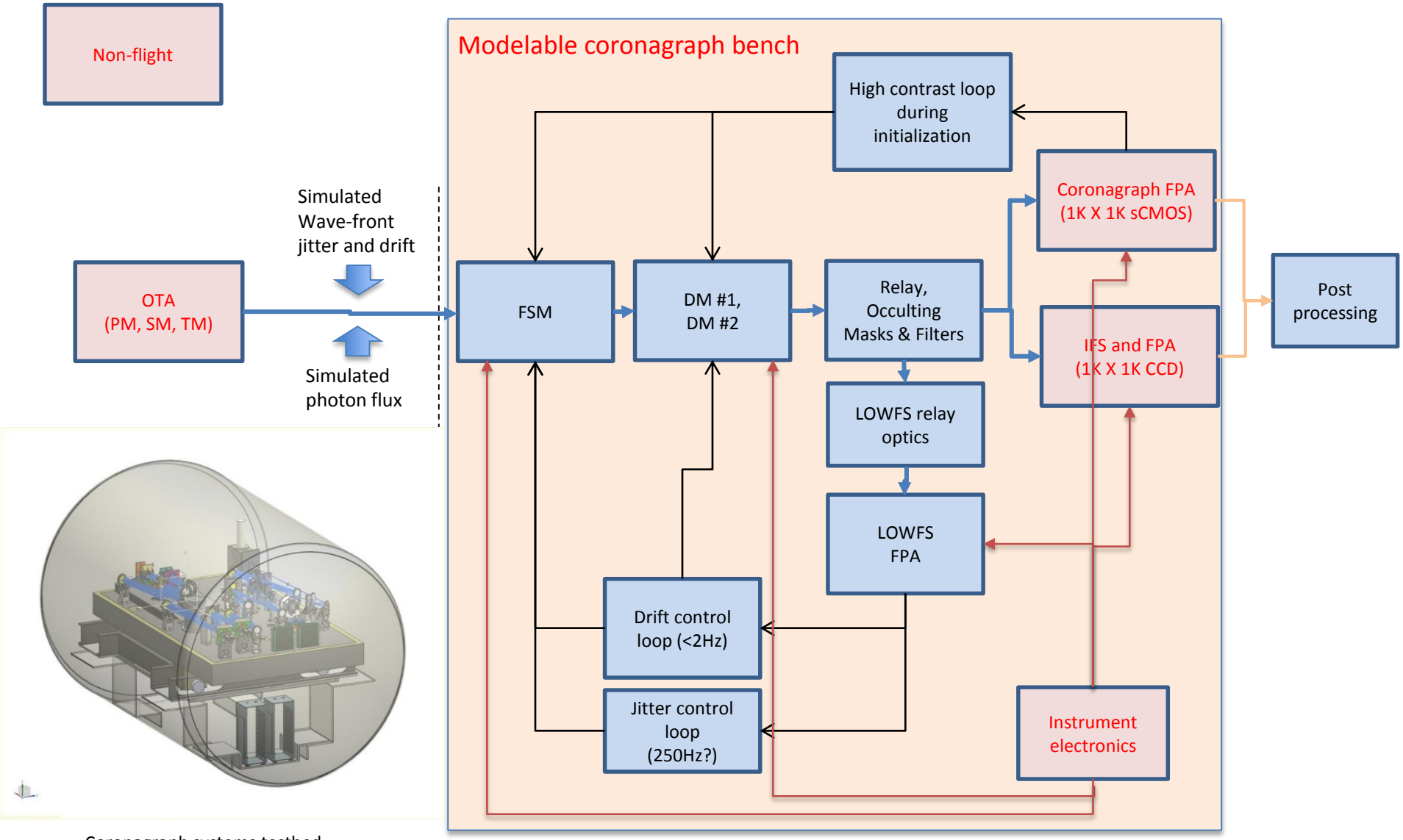
Functional Block Diagram – Flight CGI



DRM Cycle #6 CGI Design

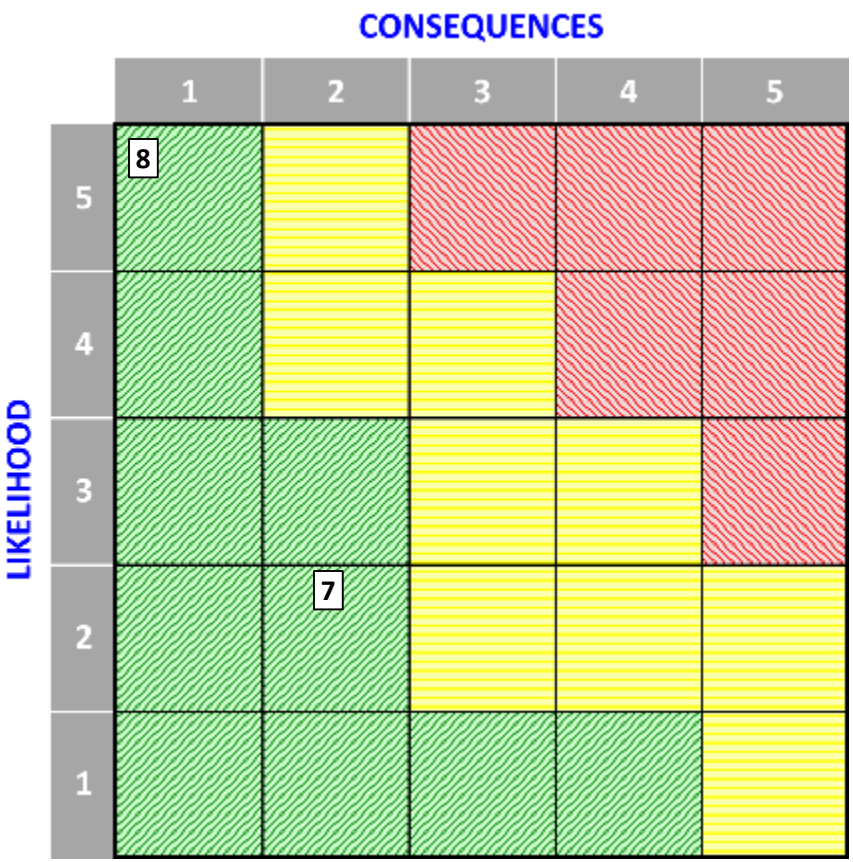


Functional Block Diagram – Coronagraph Systems Testbed



WFIRST Risk Summary

STATUS AS OF: 10-1-2016



Project Rank/ Trend	ID	TITLE	APPROACH
7 ⬌	WFIRST-RISK-CG-0044	Deformable Mirror Performance Risk	Mitigate
8 ⬌	WFIRST-RISK-CG-0047	CGI Detector Radiation Effects	Mitigate

Criticality	L x C Trend	Approach
HIGH MED LOW	↓ Decreasing (Improving) ↑ Increasing (Worsening) ⬌ Unchanged NEW New since last month	M-Mitigate W-Watch A-Accept Ar-Archive

WFIRST Risk Status (4 of 4)

STATUS AS OF: 10-1-2016

Title & Rank	Risk ID	Risk Statement	Approach	Status
7 **Deformable Mirror Performance Risk** Expected Closure: Phase B (PDR)	CG-0044	**Given that:** the Deformable Mirror (DM) is the key component to control wavefront errors, **There is a possibility that:** 1. DM correction in low-order causes mid to high-order wavefront errors 2. Insufficient stroke available to correct all wavefront errors under mission assurance required derating* (TBD%)	Mitigate	• MS9 testing demonstrated removal of focus term drift with DM1. Wavefront error estimates will not be largely affected by the updated optical design (<1nm). • Stroke budget for HLC updated. Pursuing options to improve margin (testing for max allowed voltage and polishing with bias). • Very good correlation between 48.3DM measurements on VSG and in PIAACMC Test Bed. 48.4 DM measured in VSG. MS9 will address DM correction of low orders without degrading dark hole.
8 **CGI Detector Radiation Effects** Expected Closure: Phase B/C	CG-0047	**Given that:** The EMCCD is challenged by radiation-induced traps, **There is a possibility that:** the time window of possible observations may be reduced to less than six years.	Mitigate	• WFIRST Science team met on 9/23 to discuss EMCCD; science team is requesting more data on JPL initial assumptions and measurement methodology. This topic will be covered during a splinter at FSWG. Trap density requirement definition is in work. Model will be validated with experiments on low-flux testbed. JPL held internal CCB meeting to authorize collection and analysis of data on feasibility of backup detectors • Lower flux scenes have been successfully detected in radiation damaged EMCCD. CTAC Milestone #7 successfully completed. • Low flux results were peer reviewed and validated. Milestone 7, due at the end of August, will address the issue of radiation induced traps.