WFIRST/AFTA Coronagraph Technology Development: Recent Results and Plan to TRL5

Ilya Poberezhskiy[a], Feng Zhao[a], Xin An[a], Kunjithapatham Balasubramanian[a], Ruslan Belikov[b], Eric Cady[a], Richard Demers[a], Rosemary Diaz[a], Qian Gong[e] , Brian Gordon[a], Renaud Goullioud [a], Frank Greer[a], Olivier Guyon[c], Michael Hoenk[a], N. Jeremy Kasdin[d], Brian Kern[a], John Krist[a], Andreas Kuhnert[a], Michael McElwain[e], Bertrand Mennesson[a], Dwight Moody[a], Richard Muller[a], Bijan Nemati[a], Keith Patterson[a], Marshall Perrin[f], A.J. Riggs[d], Daniel Ryan[a], Byoung-Joon Seo[a], Stuart Shaklan[a], Erkin Sidick[a], Fang Shi[a], Remi Soummer[f], Hong Tang[a], John Trauger[a], J. Kent Wallace[a], Xu Wang[a], Victor White[a], Daniel Wilson[a], Karl Yee[a], Hanying Zhou[a], Neil Zimmerman[d]

[a] Jet Propulsion Laboratory, California Institute of Technology;
[b] NASA Ames Research Center; [c] University of Arizona; [d] Princeton University
[e] NASA Goddard Space Flight Center; [f] Space Telescope Science Institute

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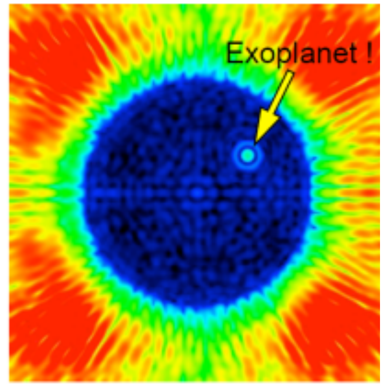
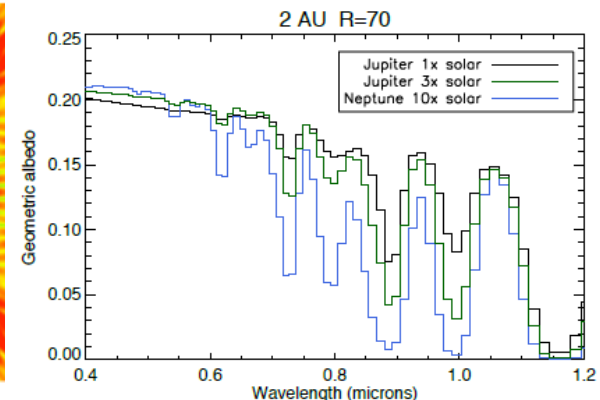
Outline

- WFIRST / AFTA Coronagraph Overview
- Shaped Pupil Coronagraph Status
- Hybrid Lyot Coronagraph Status
- Low Wavefront Sensing and Control
- Flight Instrument Design
- Integrated Modeling
- Summary

Coronagraph Technology Development



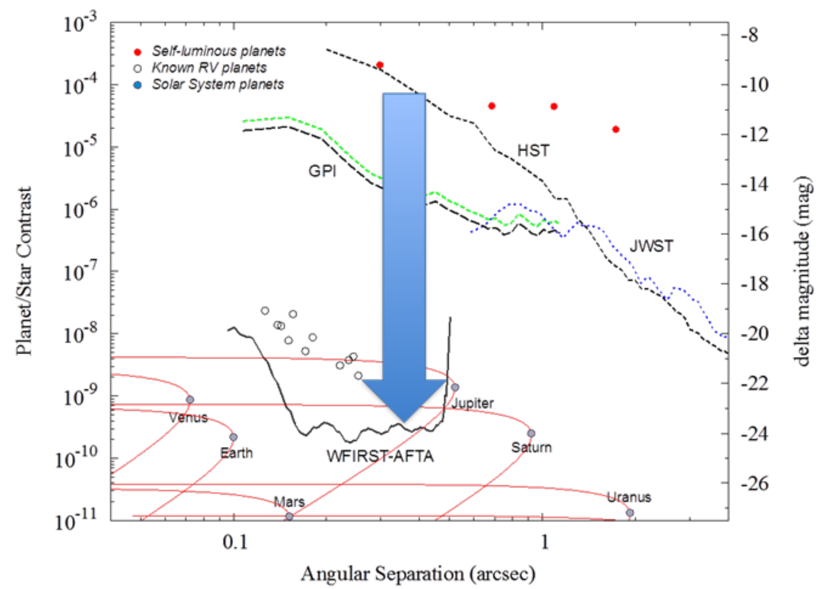


Coronagraph Instrument

Exoplanet Direct imaging

Exoplanet Spectroscopy

- WFIRST/AFTA baseline includes 1st high-contrast coronagraph in space
  - Must work with the obscured pupil 2.4 meter AFTA telescope and observatory "as is"
- Coronagraph is a tech demo, but produces precursor science
  - Exoplanet direct imaging and spectroscopy
  - Orders of magnitude improvement over existing instruments



Coronagraph Technology Development

- Technology Development Plan for maturing coronagraph technology to TRL 5 by 9/30/2016 was developed and approved
  - Working toward testbed demonstration of starlight suppression that meets science requirements in presence of optical wavefront disturbances expected on orbit
  - Mature key components – spectrograph detector and deformable mirror – to TRL6
  - 9 key milestones
  - Passed 2 of them, plan execution currently ahead of schedule

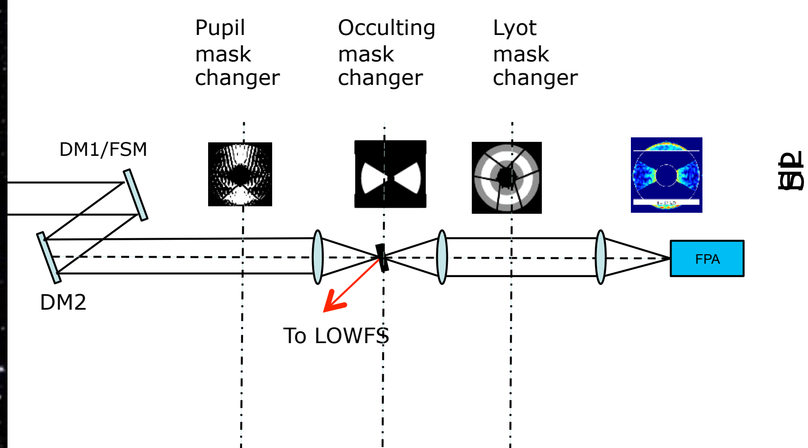
- Progress monitored by independent Technology Assessment Committee (TAC)

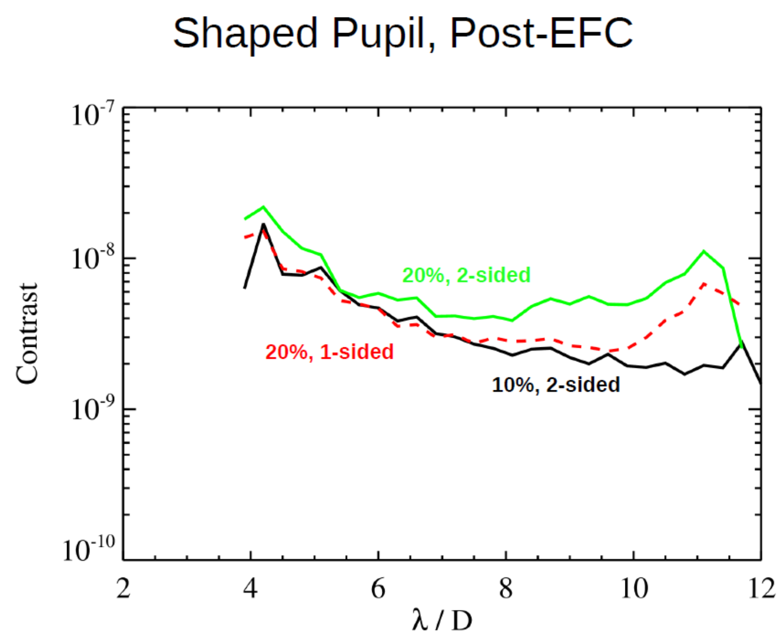
- Many institutions involved in coronagraph technology development and science

JPL Jet Propulsion Laboratory California Institute of Technology
NASA Goddard
PRINCETON UNIVERSITY
ARIZONA
NASA Ames Research Center
Stanford University
NExScI NASA Exoplanet Science Institute
ipac Infrared Processing and Analysis Center
SPACE TELESCOPE SCIENCE INSTITUTE

Selected Architecture: Occulting Mask Coronagraph

- Primary 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," OMC affords 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," 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.

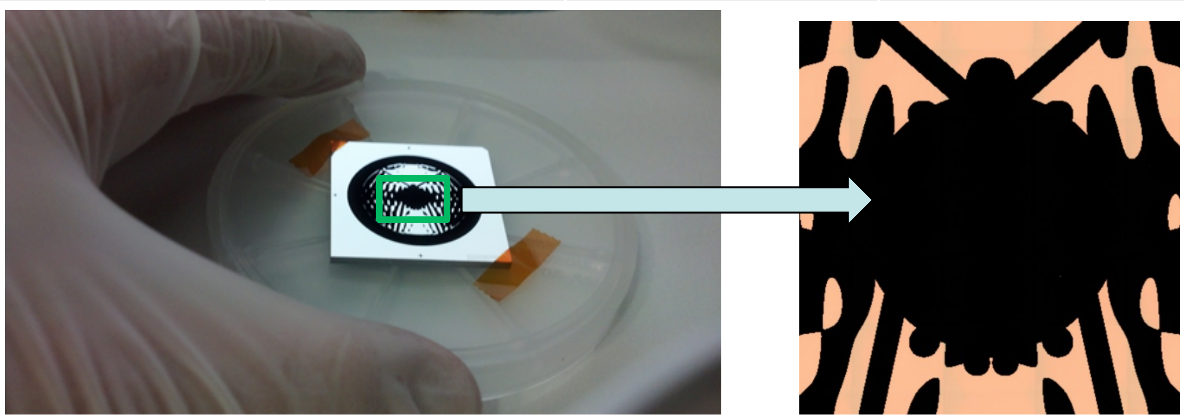




Milestone 1: Reflective Shaped Pupil Mask

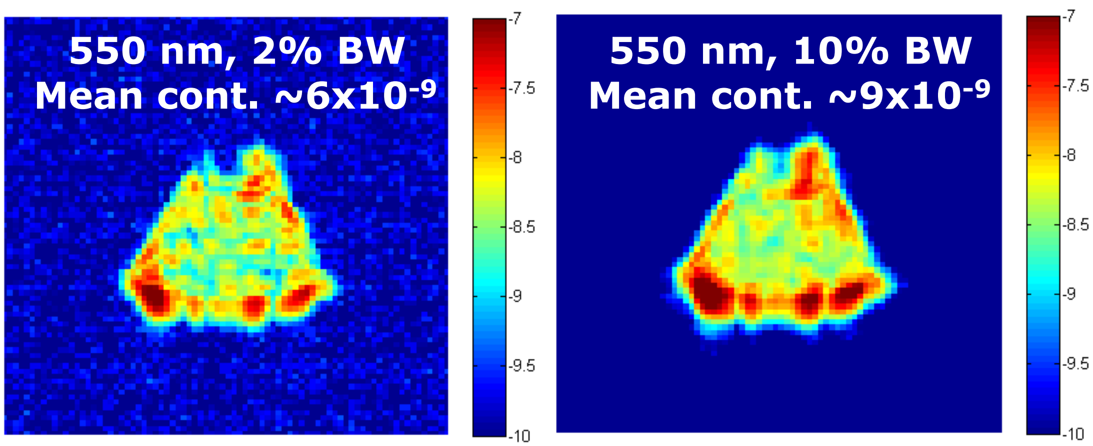
- SPC masks designed at Princeton and manufactured at JPL
- Reflective aluminum on highly absorptive black silicon
- Characterized effects of mask imperfections on coronagraph contrast
- Milestone 1 results submitted on 6/16/2014, approved by TAC

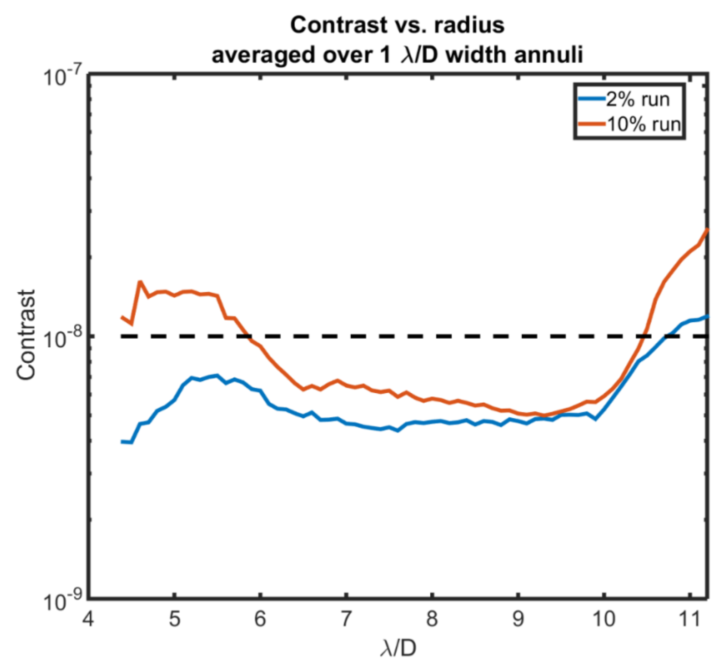
Imperfection Type	Measured Level	Delta contrast after WFC	Comments
Black Si refl., specular	$<7\times10^{-8}$	$<2.1\times10^{-10}$	Upper bound; limited by measurement setup
Black Si refl., diffuse	<0.6%	$<10^{-11}$	
Mask WFE	~0.036λ rms (above focus)	7×10^{-11}	- Post WF control - Better wafers received
Isolated defects	Small pinholes and 2 scratches	8×10^{-12}	Post WF control
Al refl. variations	~0.5%	fully correctable	Post WF control
Total		**$<3\times10^{-10}$**	**Upper bound**



Milestone 2: SPC Testbed Demonstration

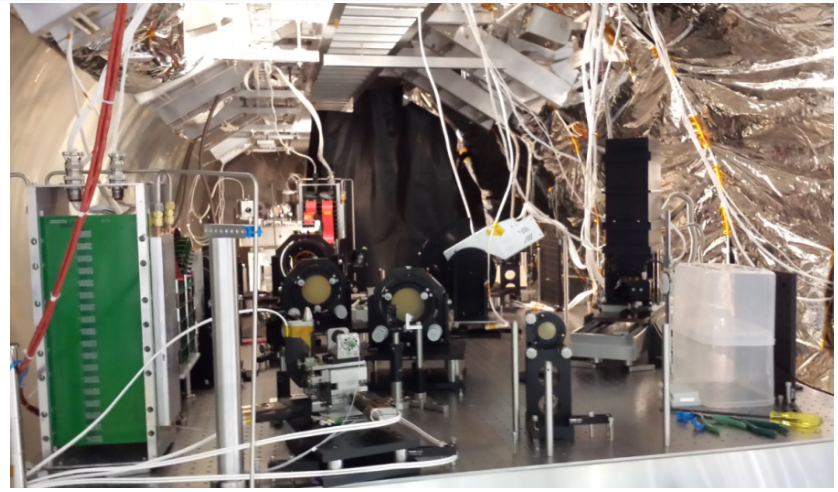
- Obtained narrowband (2%) and early broadband (10%) starlight suppression results in the shaped pupil coronagraph testbed
  - Initially with 1 DM, stopped down to 48x48 actuators
  - Milestone 2 results submitted on 9/17/14, approved by TAC
  - Broadband result meets Milestone 5 success criterion 12 months early
- **Retired the biggest technology development risk, proving that high contrast is achievable with the obscured AFTA telescope pupil**
- Starting fabrication of Gen 2 SPC masks (with Lyot stop) designed at Princeton for improved IWA and throughput

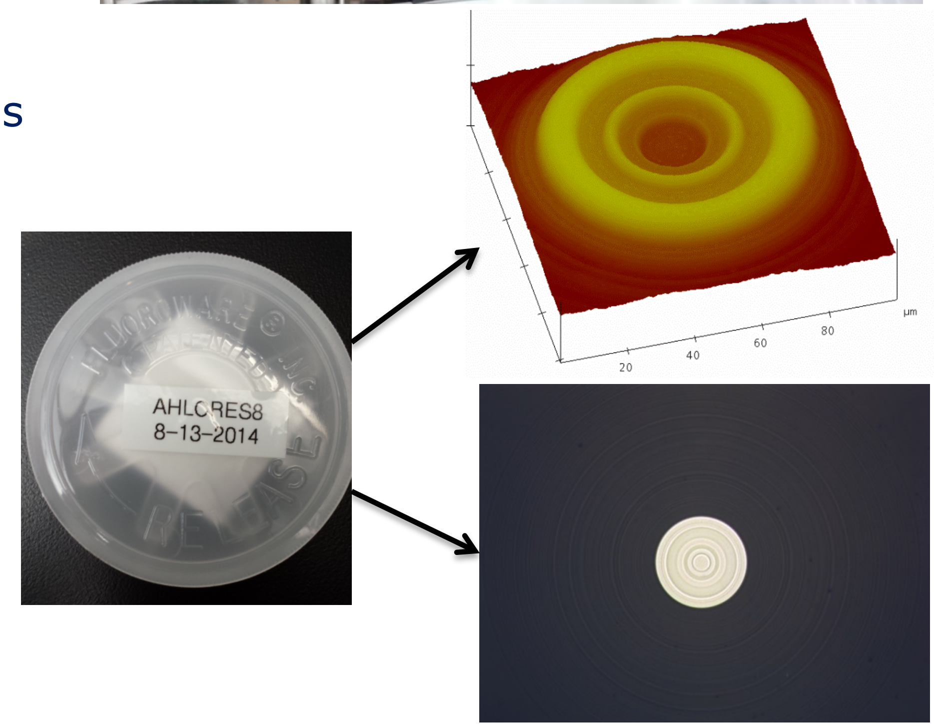




Hybrid Lyot Mask and Testbed

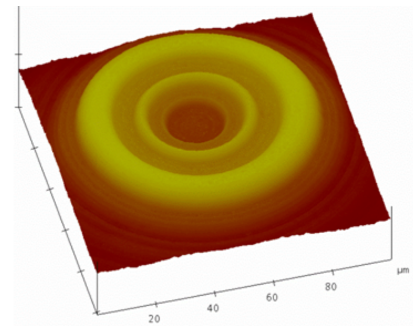
- **Circular HLC mask successfully fabricated and characterized**
  - Modeling of mask imperfections predicts good contrast
- HLC testbed aligned and calibrated in a vacuum chamber – nulling experiments in progress
  - Working with two 48x48 DMs and new driving electronics
- Milestone 4 (HLC narrowband contrast) due 2/28/2015

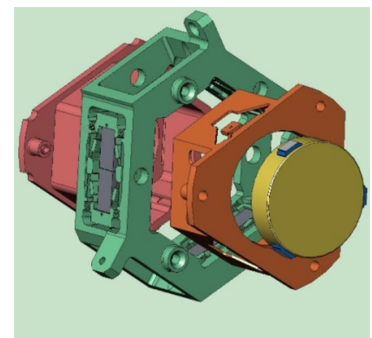


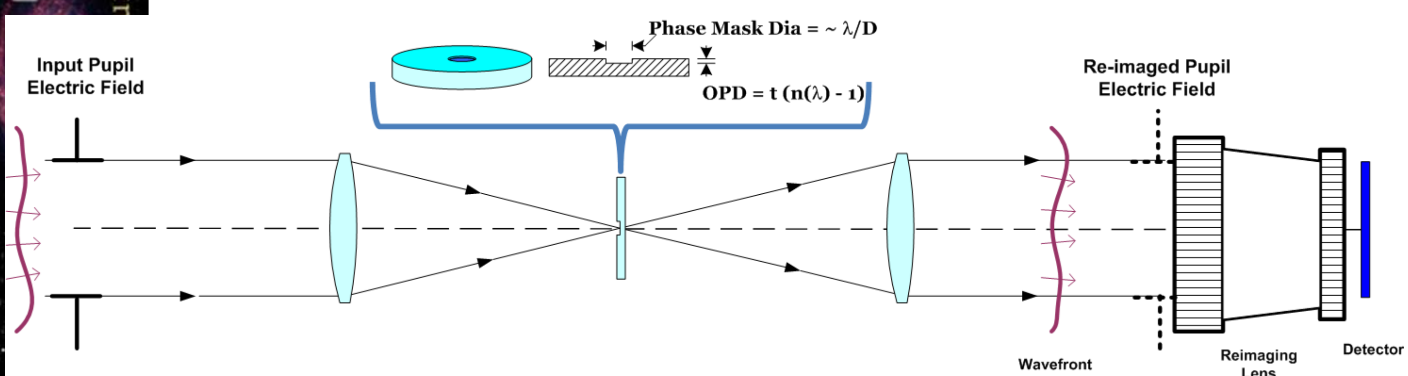


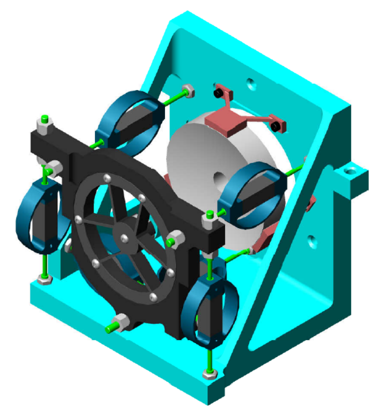
Low Order Wavefront Sensing / Control

- **LOWFS/C uses rejected starlight from the coronagraph**
  - Picked up from focal plane occulter (HLC) or field stop (SPC)
  - Senses and corrects LoS jitter, senses Z4-Z11
- **Selected Zernike wavefront sensor**
  - Zernike phase dimple on HLC and SPC focal plane masks
  - First masks received and are being tested
- **Baselined and characterized high TRL camera and fast steering mirror inherited from SIM**
- **OTA simulator with 2'' AFTA prescription telescope**



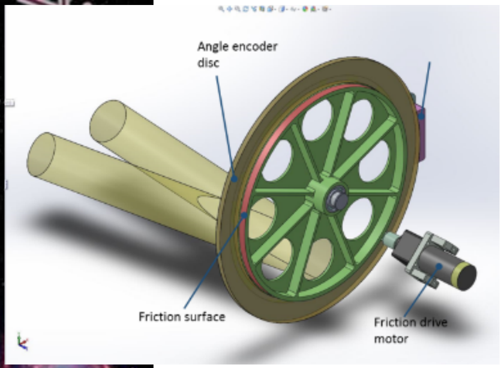


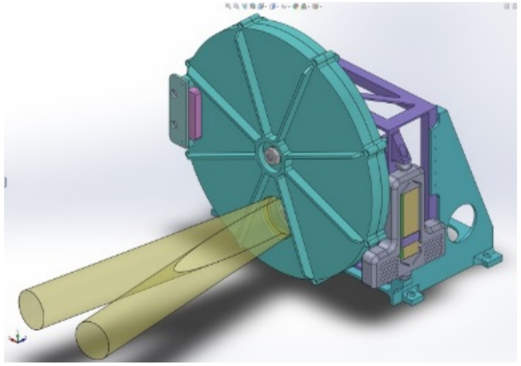


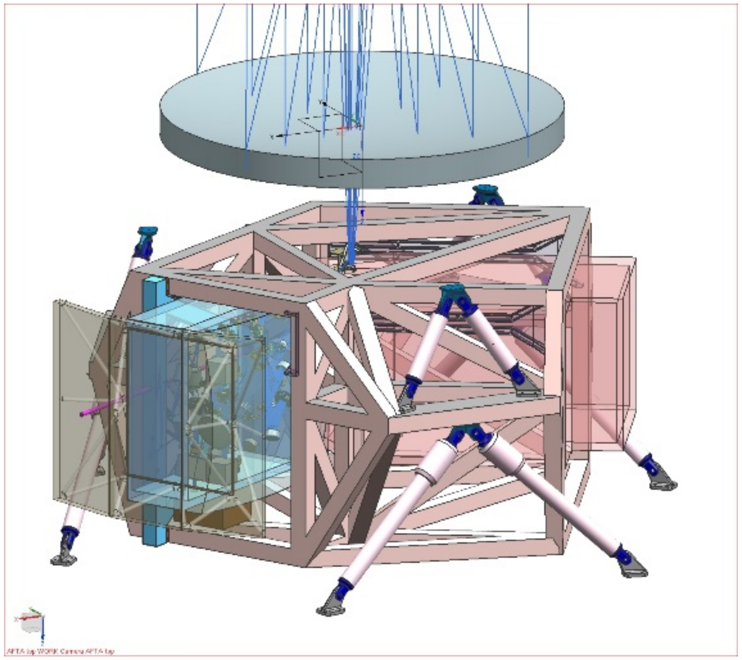


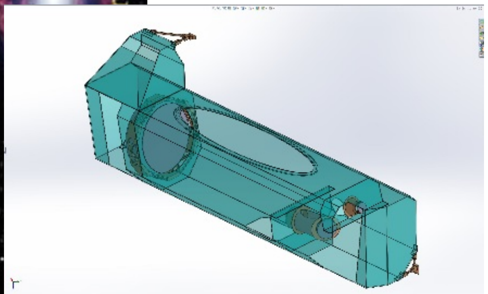
Coronagraph Flight Design

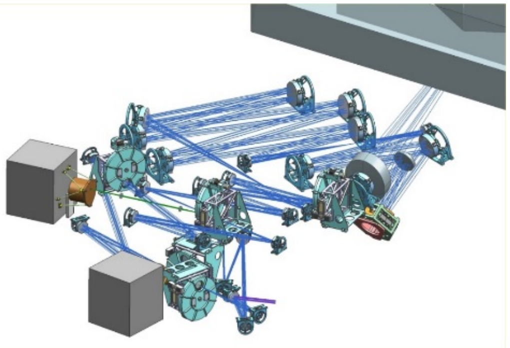
- As a tech demo, coronagraph cannot drive mission level requirements:
  - Telescope coatings, wavefront errors, obscurations
  - Observatory orbit, pointing jitter and drift, down-link
- Significant early effort to mature flight instrument design
- Our assessment is that the coronagraph will meet its performance requirements with the existing telescope and observatory constraints



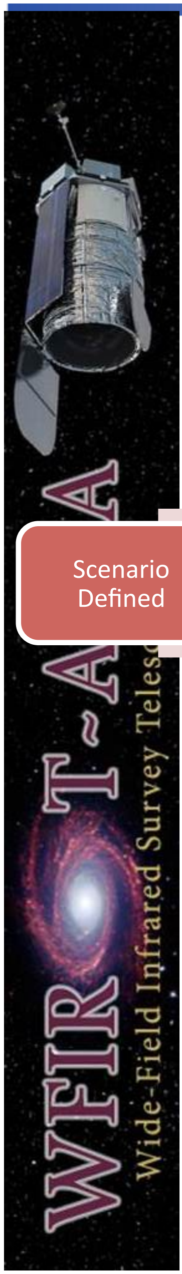




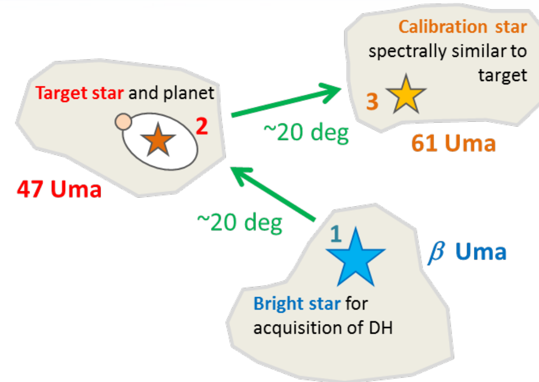


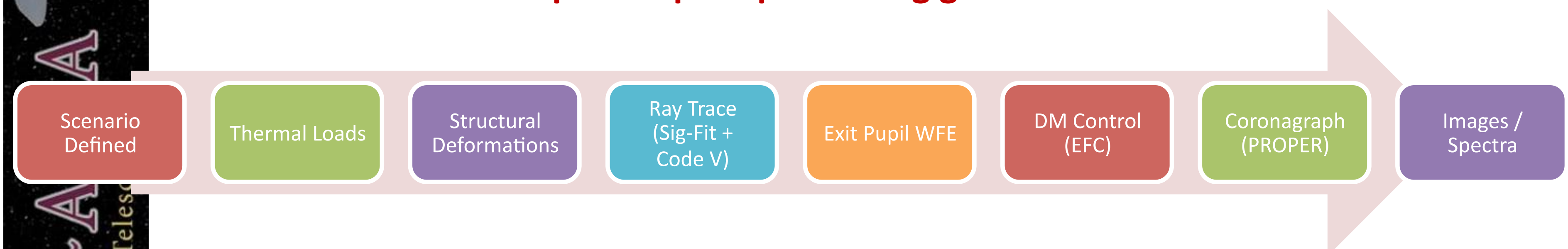


Coronagraph Integrated Modeling



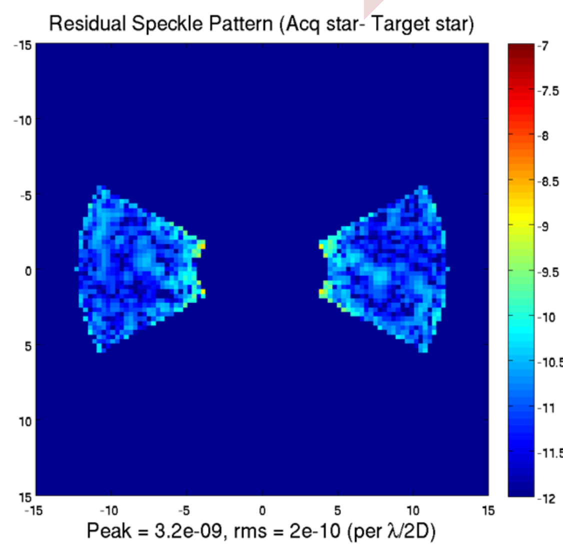
- Developed and analyzed a realistic operational scenario
  - Worst case thermal loading changes
- Integrated STOP modeling of telescope and coronagraph
- **Early results are very promising for speckle stability in the dark hole and expected post-processing gain**





- A measure of the expected post-processing effectiveness is the speckle subtracted images between two stars
- Initially, with spectra of both stars assumed flat, we find implied PP effectiveness (thermal only):

$$\boxed{f_{pp} = \frac{\sigma_{SSI}}{\langle S \rangle} \simeq \frac{1}{25}}$$



Summary

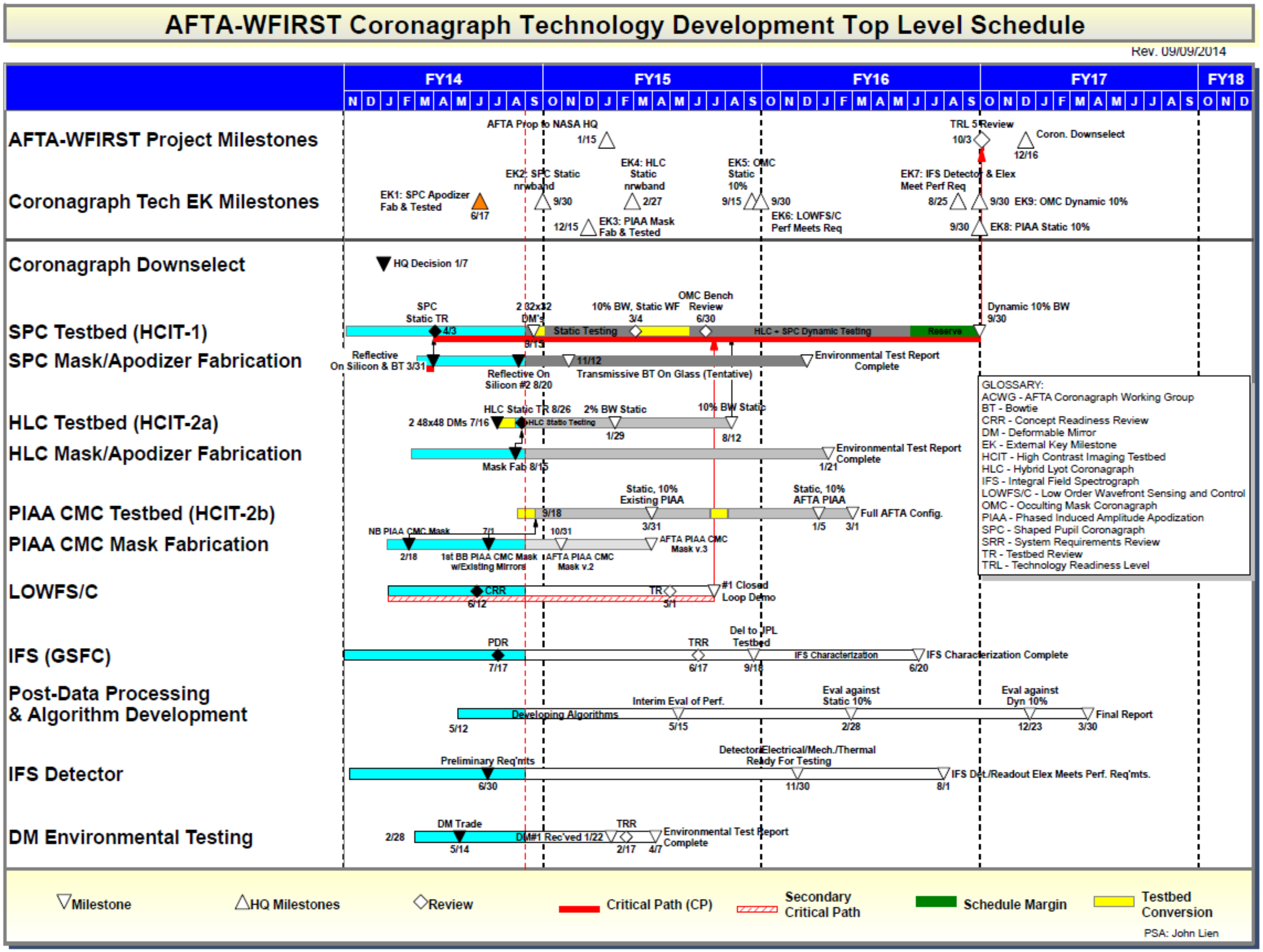
- **WFIRST-AFTA Coronagraph team is executing Technology Development Plan to mature the coronagraph to TRL 5 by 9/30/2016**
- **Work currently proceeding ahead of schedule**
- **Progress highlights in 2014:**
  - Both HLC and SPC delivered improved designs that increase science yield with obscured telescope pupil, realistic observatory jitter
  - Shaped pupil coronagraph: mask fabricated and characterized; demonstrated high contrast in testbed in 2% and 10% spectral bandpass
  - Hybrid Lyot coronagraph: circular masks fabricated and characterized, testbed nulling experiments in progress
  - LOWFS/C concept selected and is being implemented
  - Significant progress in flight instrument design and integrated modeling of the coronagraph

BACKUP

WFIRST-AFTA Coronagraph Key Milestones

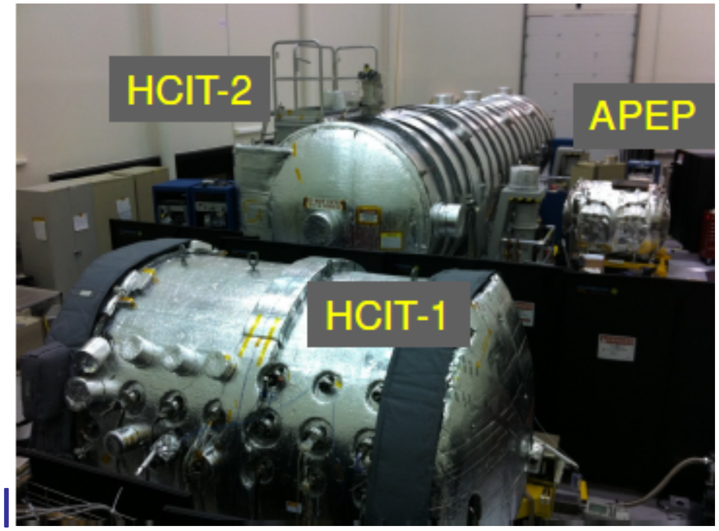
MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 µm pixel size.	7/21/14
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband 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

Top Level Technology Development Schedule

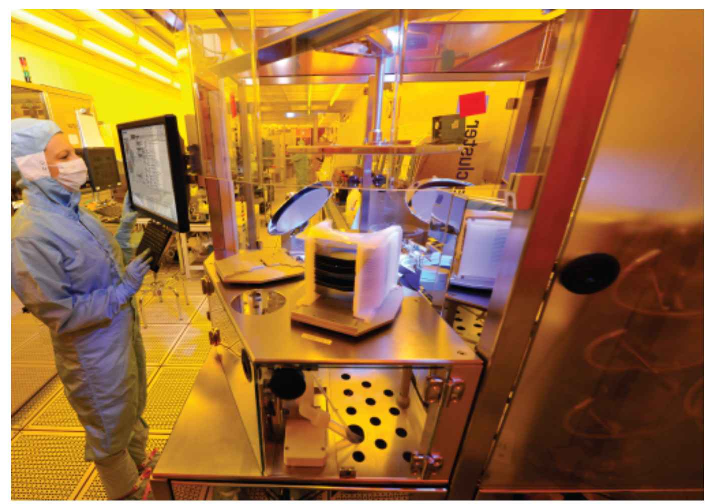


Facilities

- **Coronagraph testbeds**
  - Over a decade of successful operation at JPL
  - World record levels of contrast with unobscured and (now) obscured pupil
  - 4 testbeds operational in vacuum
  - Fully equipped, experienced personnel



- **Coronagraph Mask Fabrication**
  - Shaped pupil and hybrid Lyot masks made at MicroDevices Lab at JPL
  - World class nano-fabrication facility
  - Experienced in fabrication of flight hardware



Dynamic Broadband Demo: Milestone 9 (9/30/16)

- ***Milestone 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.
- Dynamic coronagraph testbed will be built and aligned by July 2015
- Interfaces with OTA simulator and contains LOWFS/C components
- Optical layout replicates flight OMC instrument
- Incorporates next generation of masks
- Designed with TRL5 model validation requirements in mind