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WFIRST Coronagraph Starlight Suppression Technology Progress

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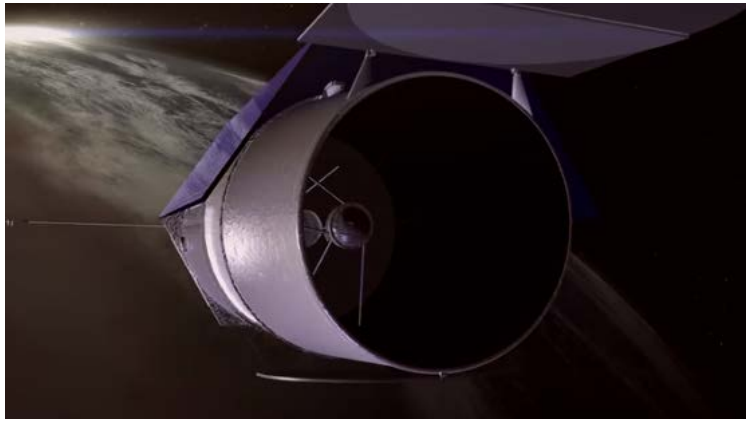
WFIRST Coronagraph Overview

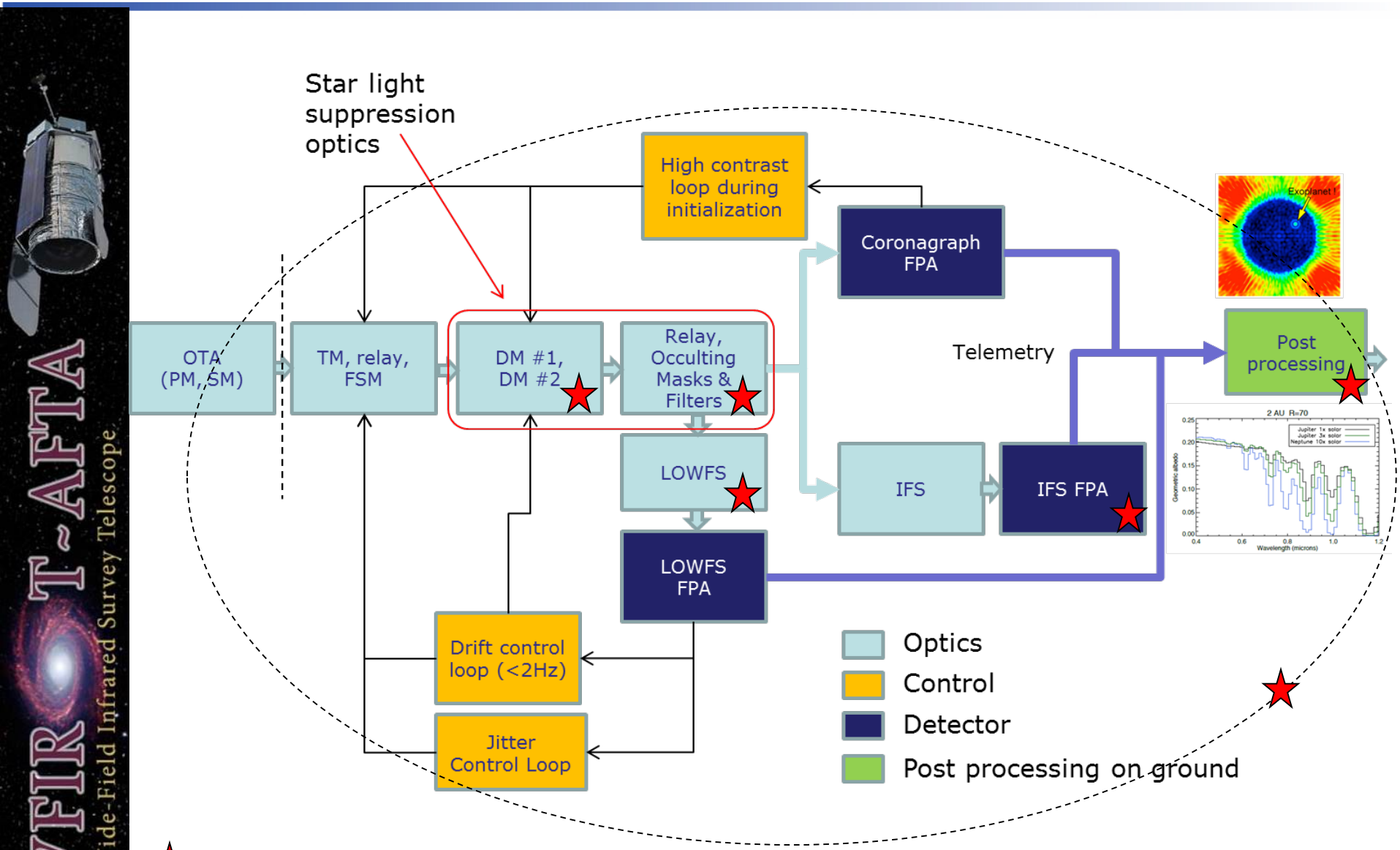
- **First high contrast, active coronagraph in space**
  - Exoplanet direct imaging technology demo
  - Precursor science for future exo-Earth mission
- Existing 2.4 meter obscured telescope
- Occulting Mask Coronagraph (OMC) as primary architecture:
  - High contrast imaging using precision wavefront sensing and control with 2 deformable mirrors
  - Shaped pupil and hybrid Lyot coronagraph masks
- PIAACMC selected as the backup architecture
- JPL led team with participation from:

  Princeton University, University of Arizona, NASA Goddard, NASA Ames, STScI, Caltech/IPAC, Northrop-Grumman Xinetics, e2v



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/Dλ (IFS)
IFS Spatial Sampling	17 mas	3 lenslets per λ/D, better than Nyquist

Coronagraph Functional Block Diagram



Coronagraph Technology Development Sequence

12/2013

Coronagraph designs that work with AFTA telescope developed, validated by modeling

12/2014

Fabrication of novel coronagraph components: masks and apodizers demonstrated

2/2015

Narrowband coronagraph contrast demonstration in the testbeds

9/2015

Broadband coronagraph contrast demonstration in the testbeds

Broadband coronagraph contrast demonstration in the testbed with representative optical wavefront disturbances (TRL 5)

TRL 6 demonstration on in critical environment

Each milestone is a necessary precondition for the following ones

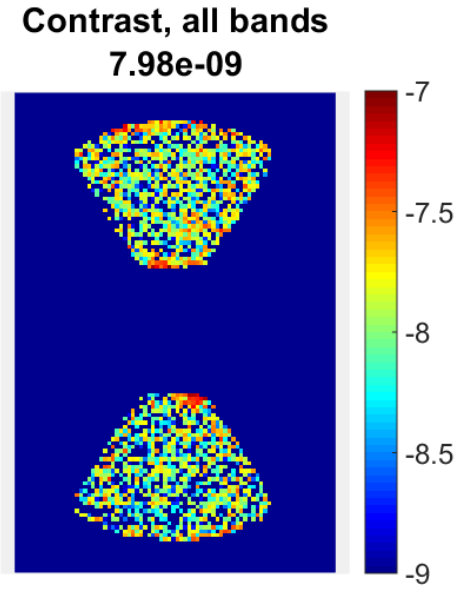
Reports available in: http://wfirst.gsfc.nasa.gov/library.html

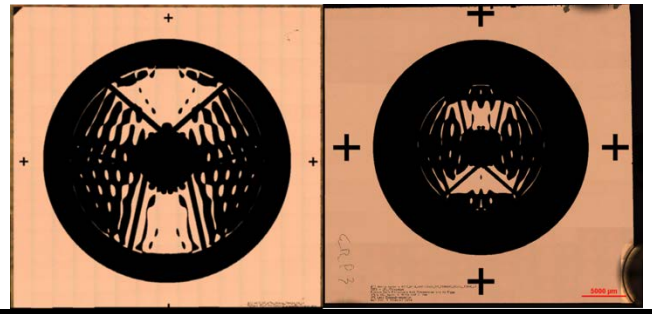
Milestones Tracking WFIRST Coronagraph TRL-5 Progress

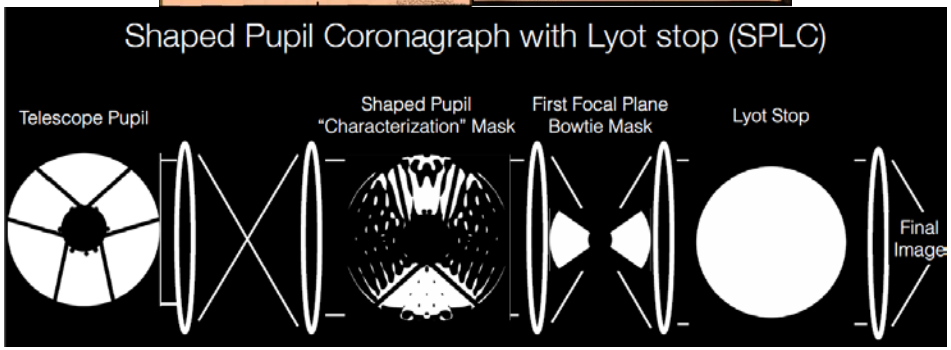
MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 μm pixel size.	7/21/14 DONE
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14 DONE
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 DONE
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 DONE
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 DONE
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 DONE
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

Shaped Pupil Coronagraph Status

- Mastered fabrication of reflective shaped pupil masks at JPL's Microdevices Lab
  - Black Silicon provides extremely low specular reflectance < 1e-8
- Milestone 5 testbed result from September 2015:
  - 8×10^{-9} narrowband contrast across a 2.8-8.8 λ/D
  - 2 DMs -> 2-sided wedge-shaped dark hole, 65° openings
- Made masks with Zernike low order wavefront sensor built in
- Currently working on high contrast demonstration with realistic on orbit input wavefront disturbances

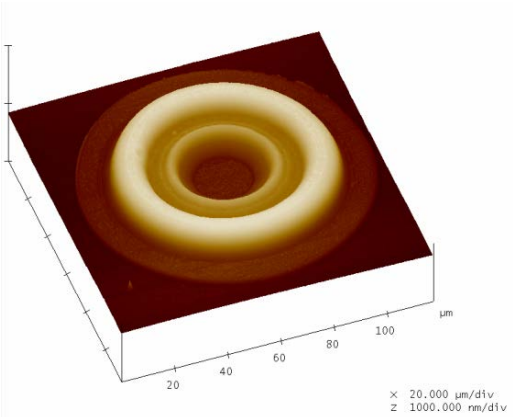


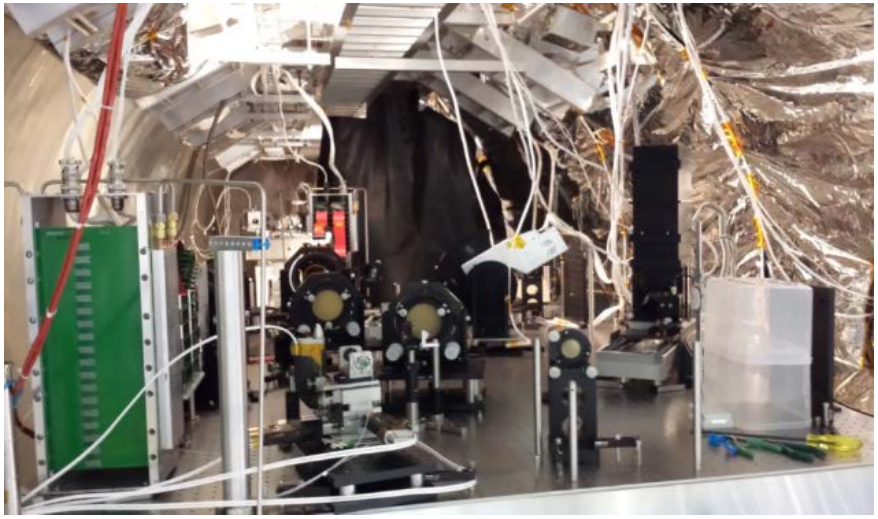




Hybrid Lyot Coronagraph Status

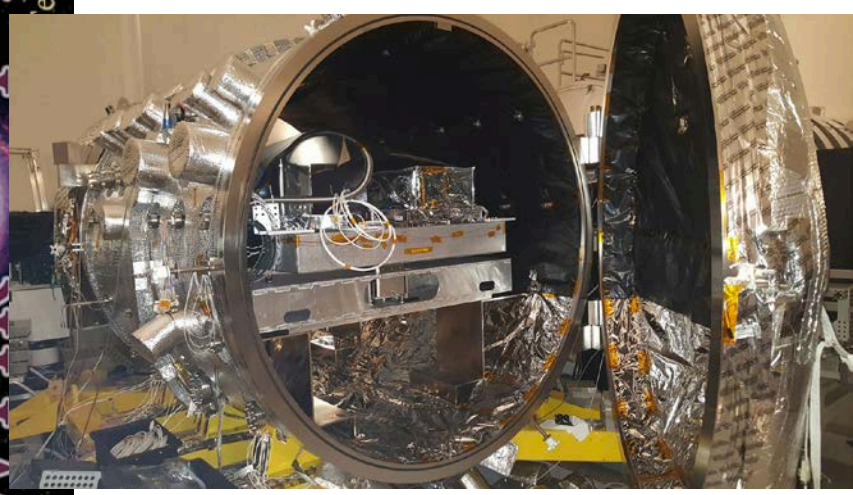
- Mastered fabrication of circular HLC occulting masks at JPL's Microdevices Lab
  - Successfully completed dielectric radiation testing
  - Zernike wavefront sensor mask built in
- Demonstrated 8.5×10^{-9} contrast with WFIRST pupil
  - 2 DMs, 360° dark hole, 3-9 λ/D
  - 10% broadband around 550 nm
- Currently working on high contrast demonstration with realistic on orbit wavefront disturbances

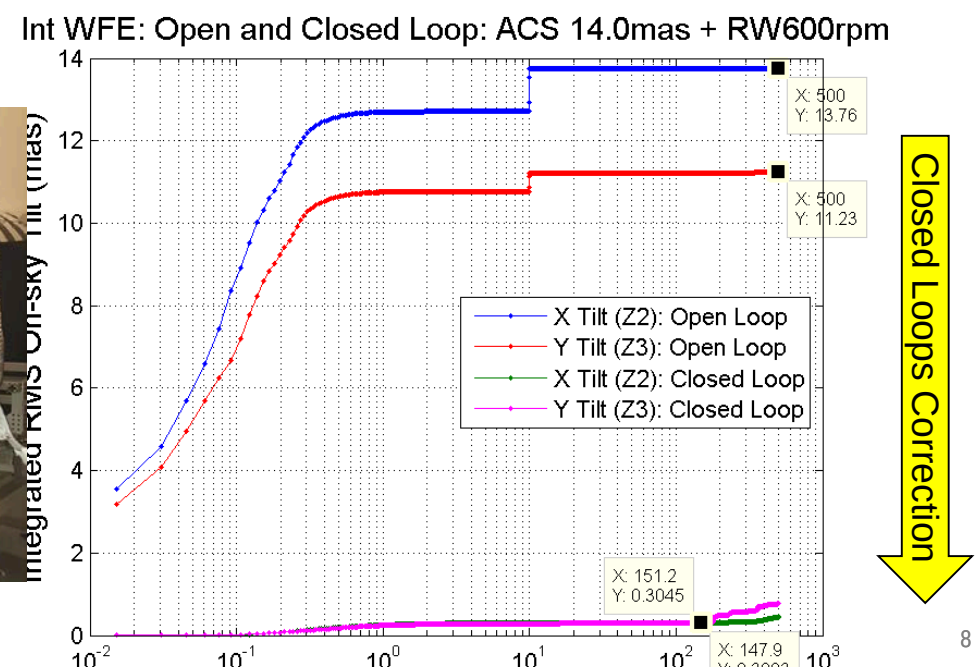




Dynamic Testbed

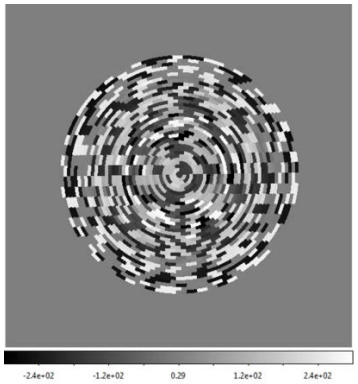
- Zernike WFS uses rejected starlight reflected by HLC and SPC coronagraph occulters
- Designed, built, aligned and calibrated LOWFS/C testbed (OTA simulator + LOWFS/C hardware)
  - Inject and correct fast pointing error, slow wavefront errors up to Z11
- Demonstrated closed loop pointing error rejection to < 0.4 mas rms on sky equivalent
- Combined with the dynamic OMC testbed, currently testing in conjunction with OMC

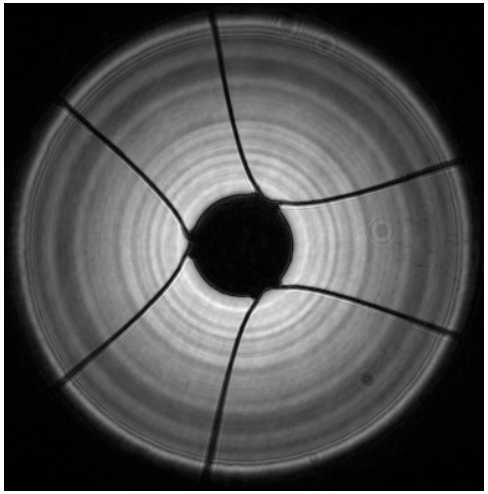


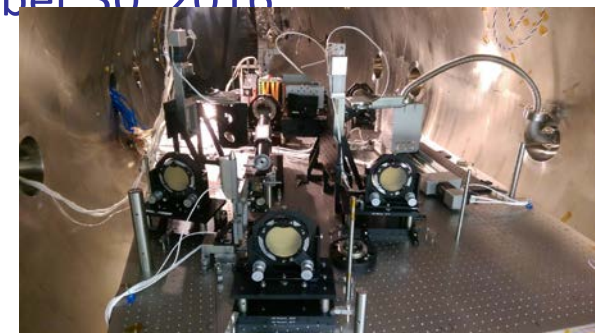


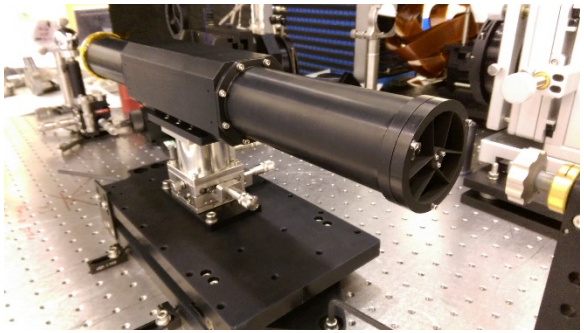
PIAACMC Status

- Backup architecture for WFIRST coronagraph
  - Much smaller inner working angle than OMC (1.3 l/D vs. 3 l/D), higher throughput
  - Greatly improved planet yield, but more vulnerable to jitter
  - Behind OMC in technology demonstration
- Passed Milestone 3 – MDL can make PIAACMC phase-only occulter to required tolerances
- PIAACMC testbed is under vacuum in HCIT, has begun work on contrast demonstration towards milestone 8 on September 30, 2016



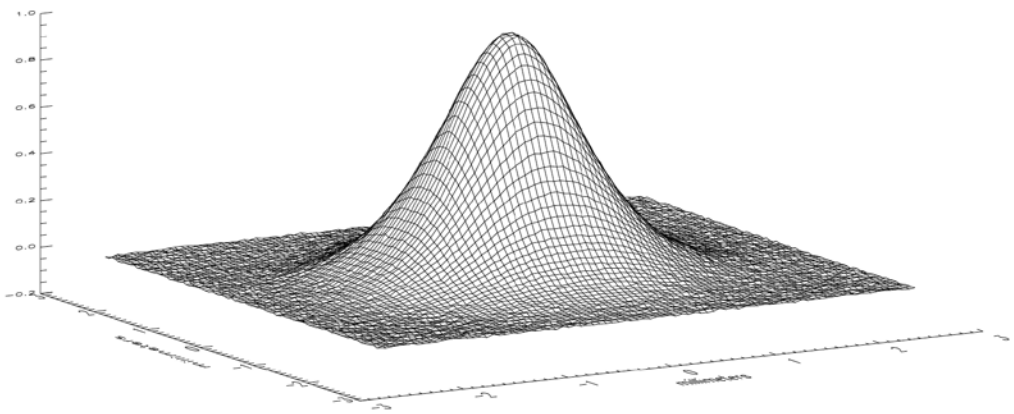


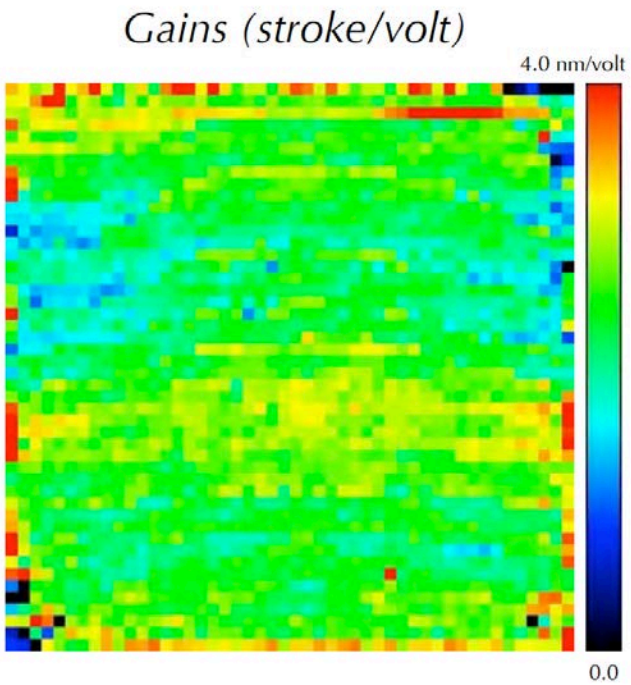




Deformable Mirror Characterization

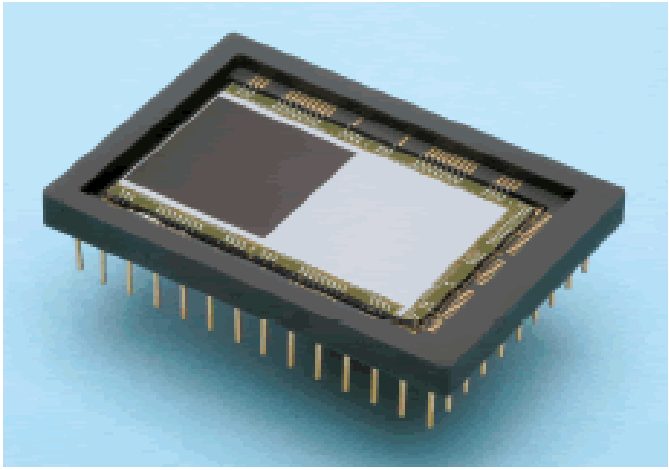
- OMC baselines two 48x48 actuator PMN deformable mirrors
- Northrop Grumman Xinetics electrostrictive deformable mirrors used since 2003 (>10^{-9} raw contrast demonstrated)
- Currently working on process improvements (e.g. interconnects)
- Commissioned interferometric Vacuum Surface Gauge facility for stand-alone DM characterization at JPL
  - 100pm class repeatability





Detector Status

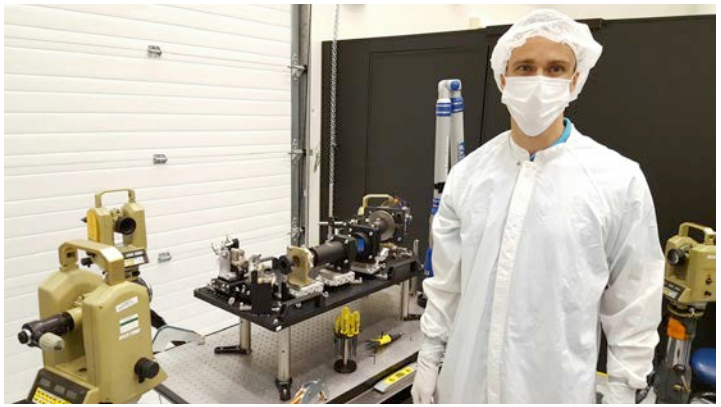
- Electron Multiplying (EM) CCD by e2v (model CCD201-20)
- **Laboratory tests show Beginning of Life (BOL) performance meets requirements**
- Radiation testing is ongoing
  - Centre for Electronic Imaging at Open University, London
- For more information: Harding et. al.



AFTA-C Detector Performance Requirements						
Specification	**Goal**	**Requirement**	**Measurement**	**Unit**	**Notes**	**Requirement met?**
Active pixels	N/A	1024×1024	1024x1024	---	---	✓
Pixel pitch	N/A	13×13	13x13	microns	Effective area: 177.2mm^2	✓
Effective read noise w/gain	0.2	0.2	<0.2	e^-	EM amp w/EM gain	✓
Dark current	1×10^{-4}	5×10^{-4}	1.01×10^{-4} *	e^-/pix/sec	***Measured at Temp 188K, IMO**	✓
Clock induced charge (CIC) @ 5σ threshold	0.0010	0.0018	0.0017	e^-/pix/fr	Measured using 10 MHz horiz. Rate, gain x1000	✓

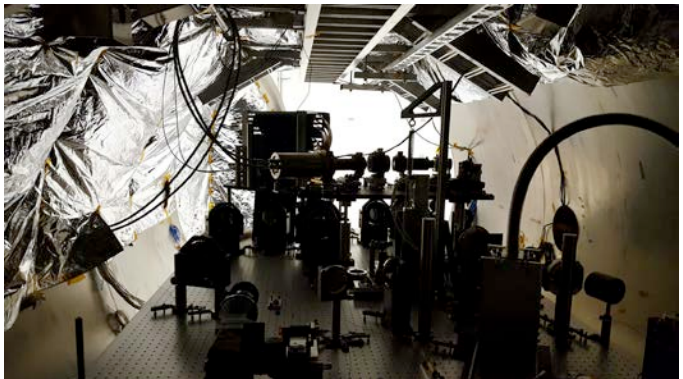
Integral Field Spectrograph Prototype

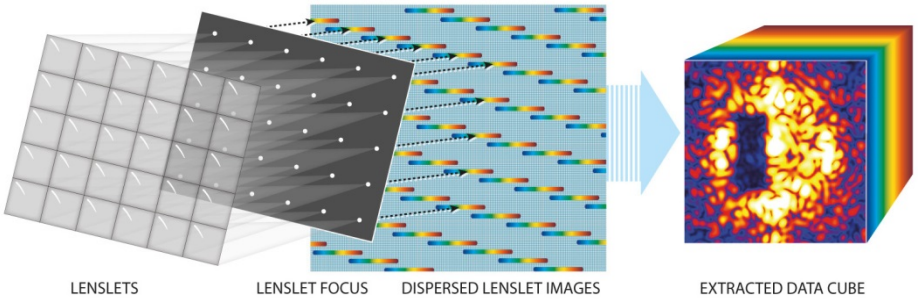
- Delivered to JPL from GSFC in June 2016, integrated with SPC testbed
- Optics design matches flight CGI baseline with three 18% spectral bands
- Currently being commissioned
- Plan to demonstrate PISCES for SPC wavefront control



IFS Specifications			
Central 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
f/#	870	870	870
Lenslet pitch (µm)	174	174	174
sampling at λ_c	3.3	3.9	4.6
FOV (# of λ_c/D*) [diameter]	23.2	19.6	16.6
FOV (arcsec) [diameter]	1.3	1.3	1.3

* λ/D, not 1.22λ/D





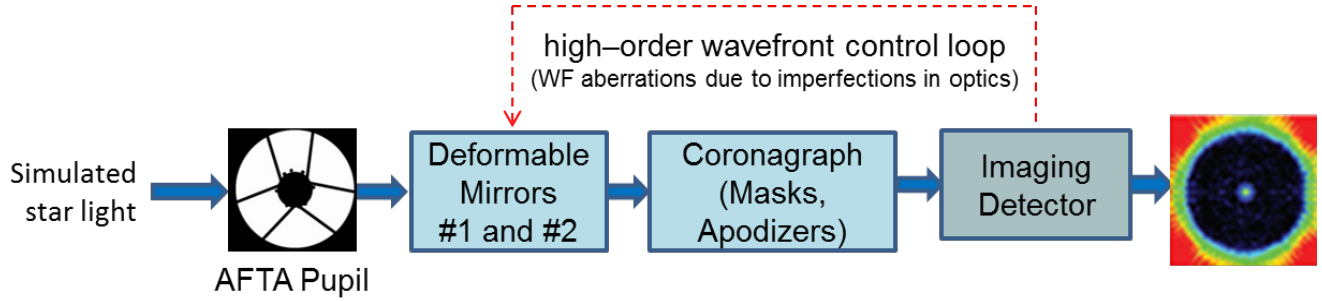
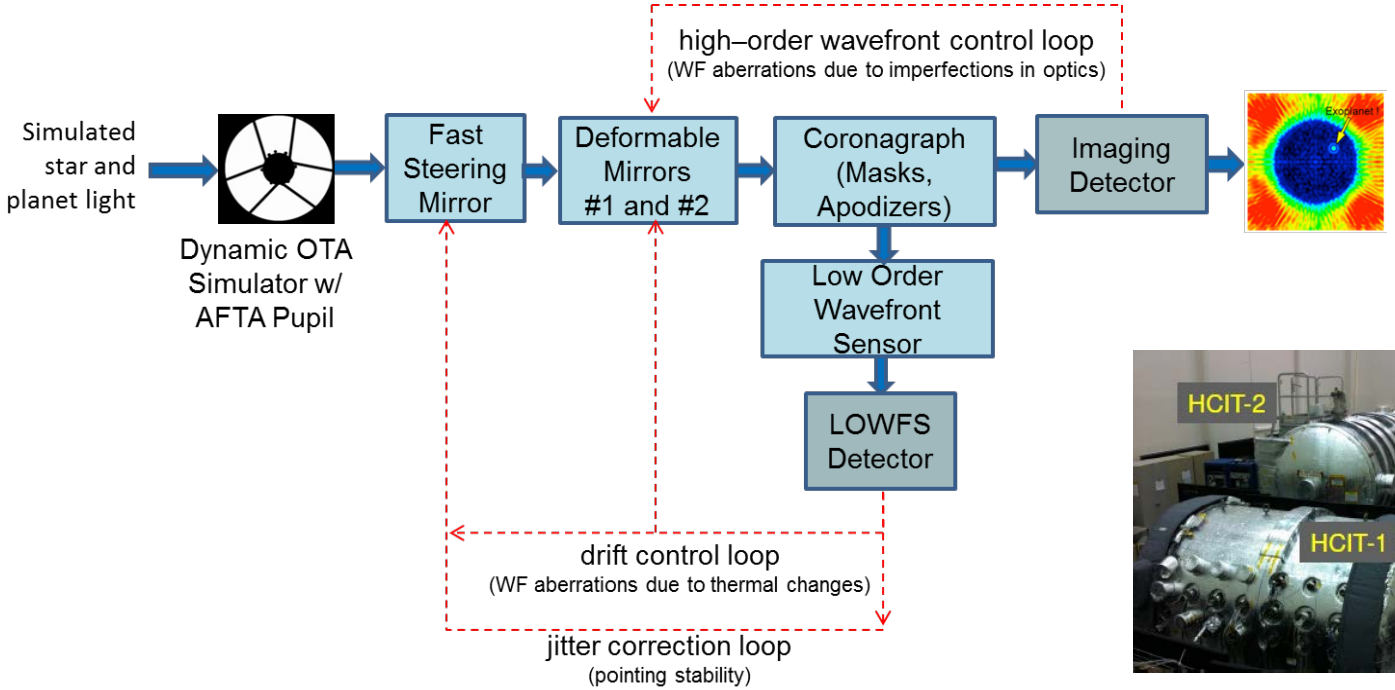
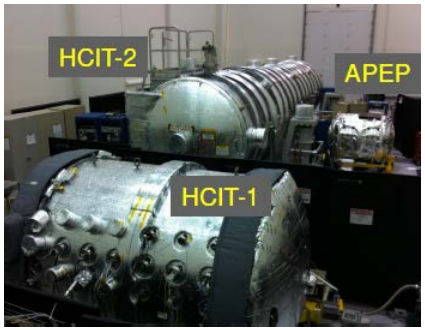
Summary

- WFIRST coronagraph technology development progressing on schedule according to NASA plan from 2/2014
  - Demonstrated fabrication of all needed starlight suppression masks
  - Met first 6 out of 9 NASA milestones on time
  - Key components – low noise detector and deformable mirror – are matured in parallel with testbed work
- Broadband high contrast <10^-8 demonstrated with WFIRST obscured pupil by both primary coronagraph modes: HLC and SPC
- Closed loop pointing control with Low Order Wavefront Sensor demonstrated in a stand-alone testbed; recently combined with the coronagraph
- PIAACMC being matured as a backup technology
- OMC broadband high contrast demonstrations in a realistic dynamic environment are proceeding toward Milestone 9 in September 2016 (WFIRST coronagraph technology at TRL5)

BACKUP SLIDES

Static and Dynamic OMC Demonstrations

- **Static 10% broadband contrast demonstration (Milestone 5) due 09/15/2015**



- **Dynamic 10% broadband contrast demonstration (Milestone 9) due 09/30/2016**