Starshade and Coronagraph Technology Gaps and Paths to Close Them

Peter Lawson and Nick Siegler

NASA Exoplanet Exploration Program Analysis Group Meeting (ExoPAG) 8

Denver, Colorado

6 October 2013

Starshade Technology Gaps

- **High Relative Gap and Urgency**
  - System engineering, I&T Verification and Validation (SG-1)
  - Control of scattered light from petal edges (SG-5)

- **Medium Relative Gap and High Urgency**
  - Starshade deployment demonstration (SG-3)

Importance:	H	Showstopper
	M	Major regret
	L	Not H or M
Urgency	H	Retire by 2015
	M	Retire by start Phase A (fy17)
	L	Retire by start of Phase B (fy19)

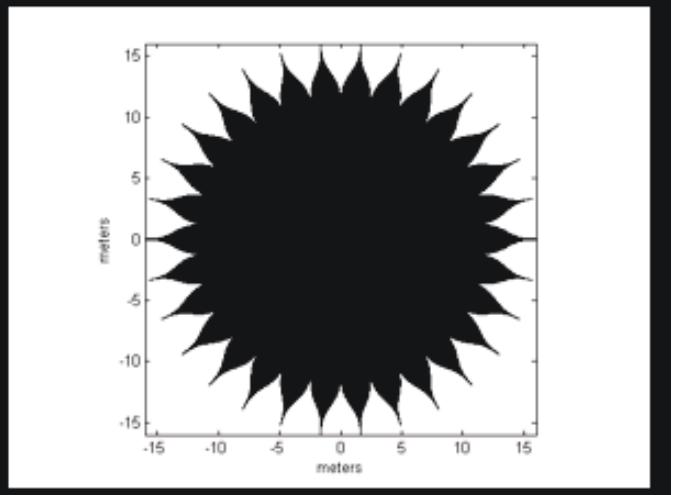
- **Medium Relative Gap and Medium Urgency**
  - Validation of starshade models (SG-4)
  - Thermal and dynamic stability under flight conditions (SG-9)

- **Technologies with Lower Relative Gap**
  - Formation sensing for a dedicated telescope (SG-7)
  - Thruster technology for slew and science observations (SG-10)
  - Guidance, Navigation and Control for retargeting (SG-6)
  - Petal manufacturing (SG-2)

Starshade Technology

Technology Challenges

To design and build an occulter that can fit in a launch fairing (preferably with the telescope) and satisfies the requirements and constraints on:



- Precision edge shape manufacture (TDEM-1)
- Deployment accuracy (TDEM-2)
- Validated optical models (software and lab) SPIE 8864-43
- Sharp edges to minimize solar glint SPIE 8864-44
- Sensing and Formation control
- Thermal and Dynamic stability

Kasdin et al. “Verifying occulter deployment tolerances…” SPIE (2013)

AFTA Coronagraph Technology Gaps

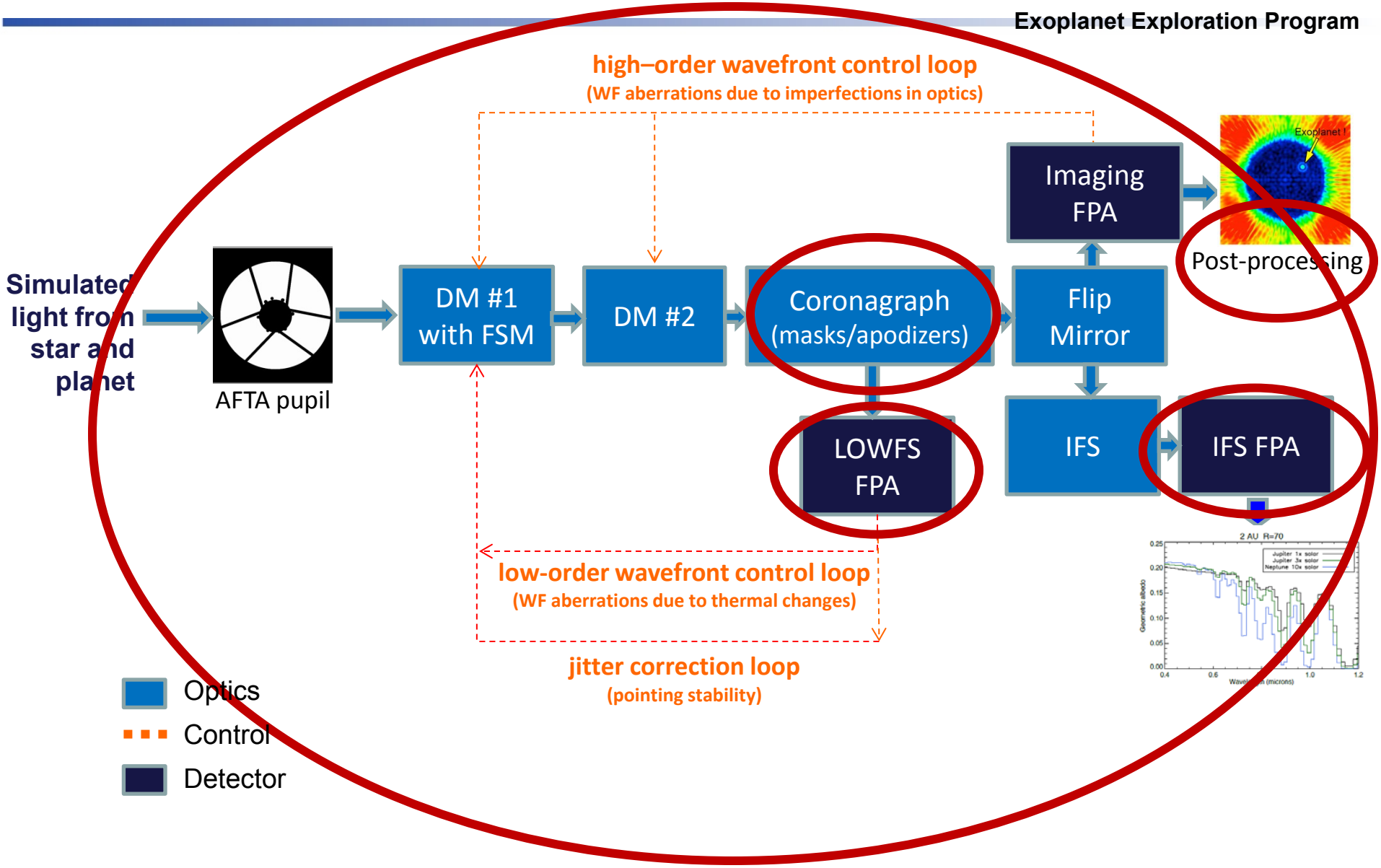
- **High Relative Gap and Urgency**
  - Architecture design (CG-1a)
  - Key component fabrication (CG-1b)
  - Contrast demonstrations (CG-6)
  - Low-order wavefront demonstrations (CG-2)

- **Medium Relative Gap and Urgency**
  - Flight readiness of DM and Fast Steering Mirror (CG-7)
  - Two-DM performance demonstration (CG-3)
  - End-to-end dynamic modeling (CG-5)

- **Less Urgent Gaps**
  - Post-processing of data (CG-4)
  - IFS pixel cross talk (CG-8)
  - Flight readiness of IFS detector (CG-9)
  - Demonstrations in a flight-like environment (CG-10)

Closing Technology Gaps for Flight Coronagraphs

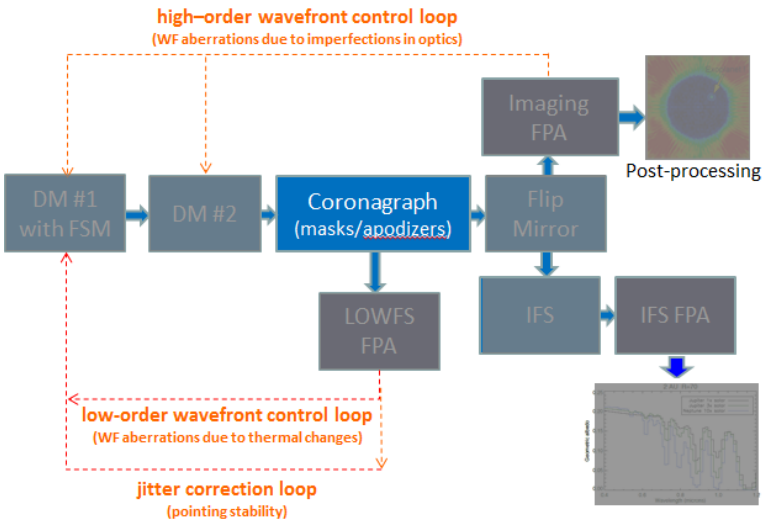
Classical Lyot Coronagraph Design

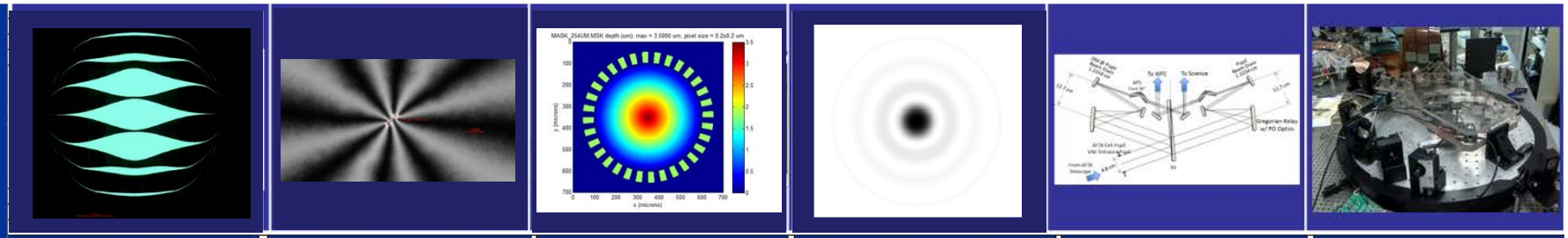


Coronagraph Architectures and Fabrication

Possible Path to Closing Gap

1. **Selection process underway from six AFTA candidate coronagraph architectures to two.**
   - Primary and backup
2. **Fabricate sets of each mask/apodizers**
3. **Demonstrate performance in the two HCITs**
   - Mask/apodizer iterations likely
4. **Radiation testing (if necessary)**
   - Some of the masks may have dielectrics or liquid crystal polymers
5. **Downselection to one**



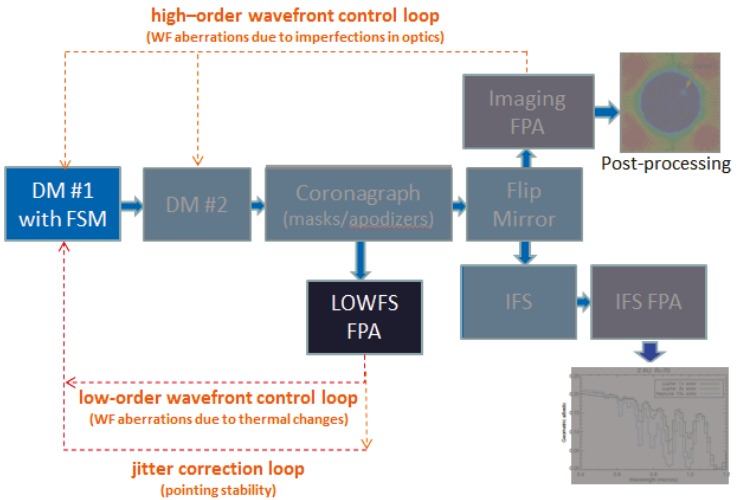


Concept Name	Shaped Pupil Maks	Vector Vortex	Phase Induced Amplitude Apodization	Hybrid/Band Limited Lyot	Visible Nulling Coronagraph – Phase Occulted	Visible Nulling Coronagraph – DaVinci
Nick Name	Shaped Pupil	VV	PIAA	Hybrid Lyot	PO-VNC	DaVinci-VNC
Advocate	Jeremy Kasdin	Gene Serabyn	Olivier Guyon	John Trauger	Rick Lyon	Mike Shao

Low-Order Wavefront Sensing and Control (LOWFS/C)

Possible Path to Closing Gap

1. **Upon AFTA coronagraph selection and receiving telescope jitter and WF drift inputs, baseline LOWFS/C rqmts for each coronagraph.**
2. **Select from multiple LOWFS/C techniques one or two.**
   - Each of the down selected coronagraphs may have different sensitivities to low-order WF aberrations.
3. **Develop LOWFS/C algorithms using modeling**
4. **Build and demonstrate LOWFS/C closed-loop performance in an independent vacuum testbed.**
5. **Deliver and integrate to HCITs**



Knife Edge
- Use image morphology from a slightly defocused PSF to sense WF
- Detector near image plane
- Can sense tilt

Zernike WFS
- Point diffraction interf.
- Sense WF by interfering the WF with a reference WF created by a spatial filter
- Detector at pupil plane
- Can sense tilt

Phase Retrieval
- Use FT and slightly defocused image to sense the WF
- Detector near image plane
- Can sense tilt

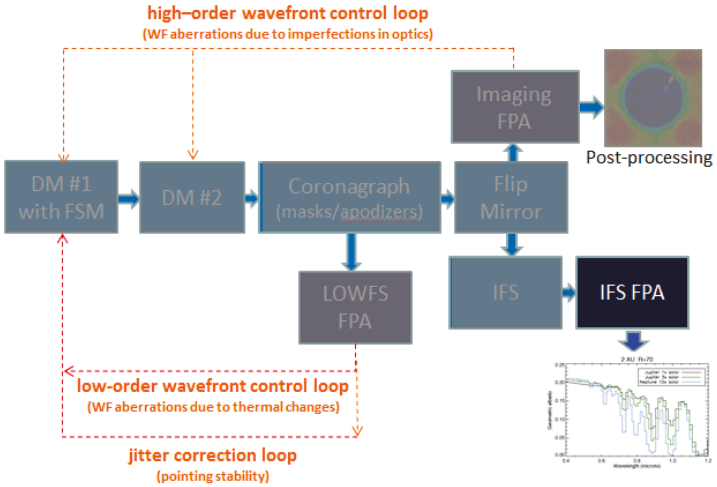
Shack-Hartmann
- Use SH subaperture image centroid to measure local WF tilt
- Detector at pupil plane
- Can sense tilt

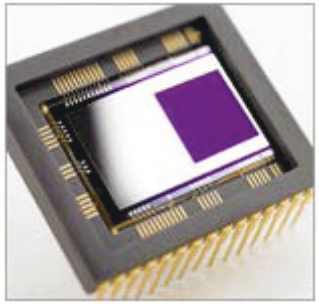
Fast WF Jitter
- PSF centroid or quad cell / pyramid APD for line of sight at high rate
- WF tilt only

IFS Ultra-Low Noise Detector

Possible Path to Closing Gap

1. **Understand science operational scenarios and camera modes; derive preliminary detector requirements.**
   - < 0.1 e/pix read noise
   - ~0.0001 e/pix/s dark current
   - QE > 80% in the visible
2. **Survey existing detector and read-out electronics technologies**
   - recommend a device that meets requirements.
3. **Acquire and test performance of available low-noise detector or camera system under realistic operational scenarios**
   - Includes low-noise electronics
4. **Select a baseline detector and read-out electronics design.**
5. **Perform radiation testing of the selected detector; before and after characterization.**
6. **Design, build, and test flight-like electronics boards.**



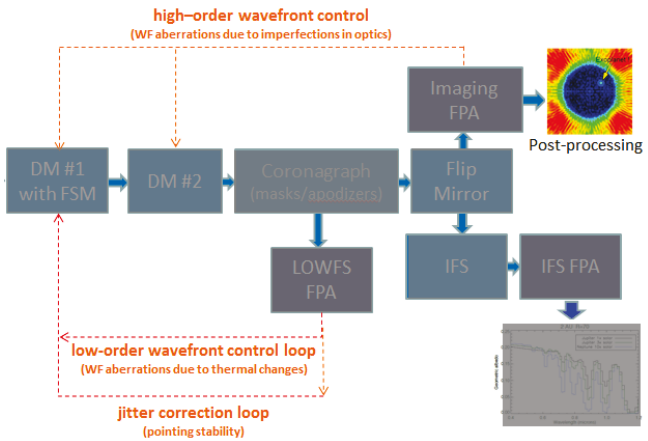


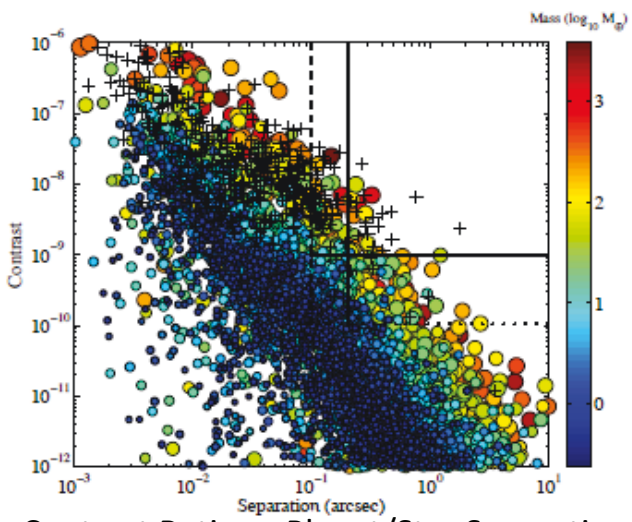
e2V Electron Multiplying CCD
(a candidate device)

Post-Data Processing

Possible Path to Closing Gap

1. **Assess the performance of current state-of-the-art post-processing algorithms using existing HCIT data and simulated multiwavelength IFS data**
   a) evaluate the regime where contrast in no longer dominated by phase errors.
2. **Understand telescope/instrument temporal behavior and assess possible operational scenarios and observation strategies**
3. **Develop simulations of realistic AFTA coronagraphic PSFs including thermal modeling, LOWFS, temporal variations.**
4. **Develop simulated PSF library from actual HCIT data with AFTA pupil.**
5. **Demonstrate algorithm by retrieving simulated planet through PSF subtraction.**



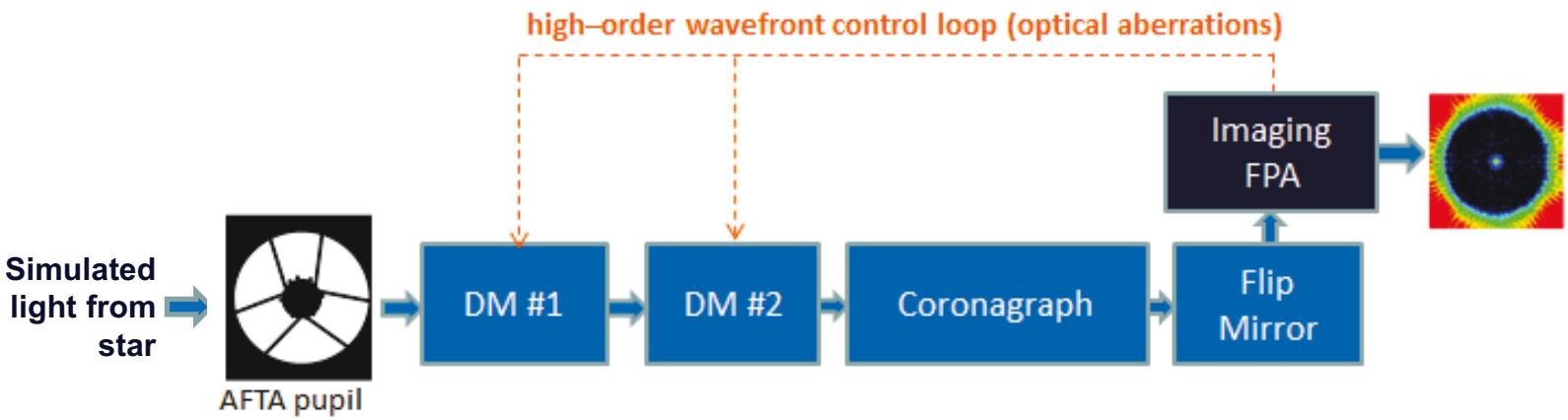


Contrast Ratio vs Planet/Star Separation
AFTA-WFIRST Study Report (2013)

Static Wavefront Systems-Level Testbed Demonstration

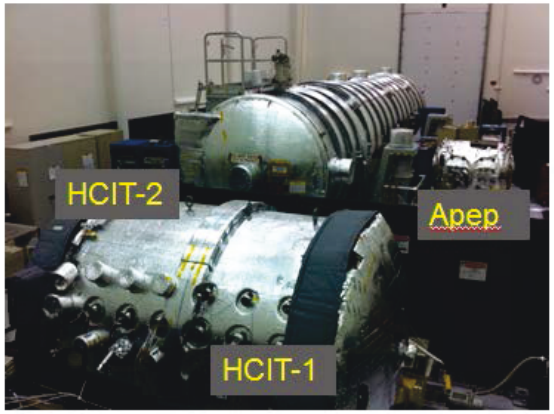
Possible Path to Closing Gap

Demonstrate static wavefront performance in fully-assembled coronagraph vacuum testbed with simulated AFTA-WFIRST telescope pupil.



Key Demonstration Objectives

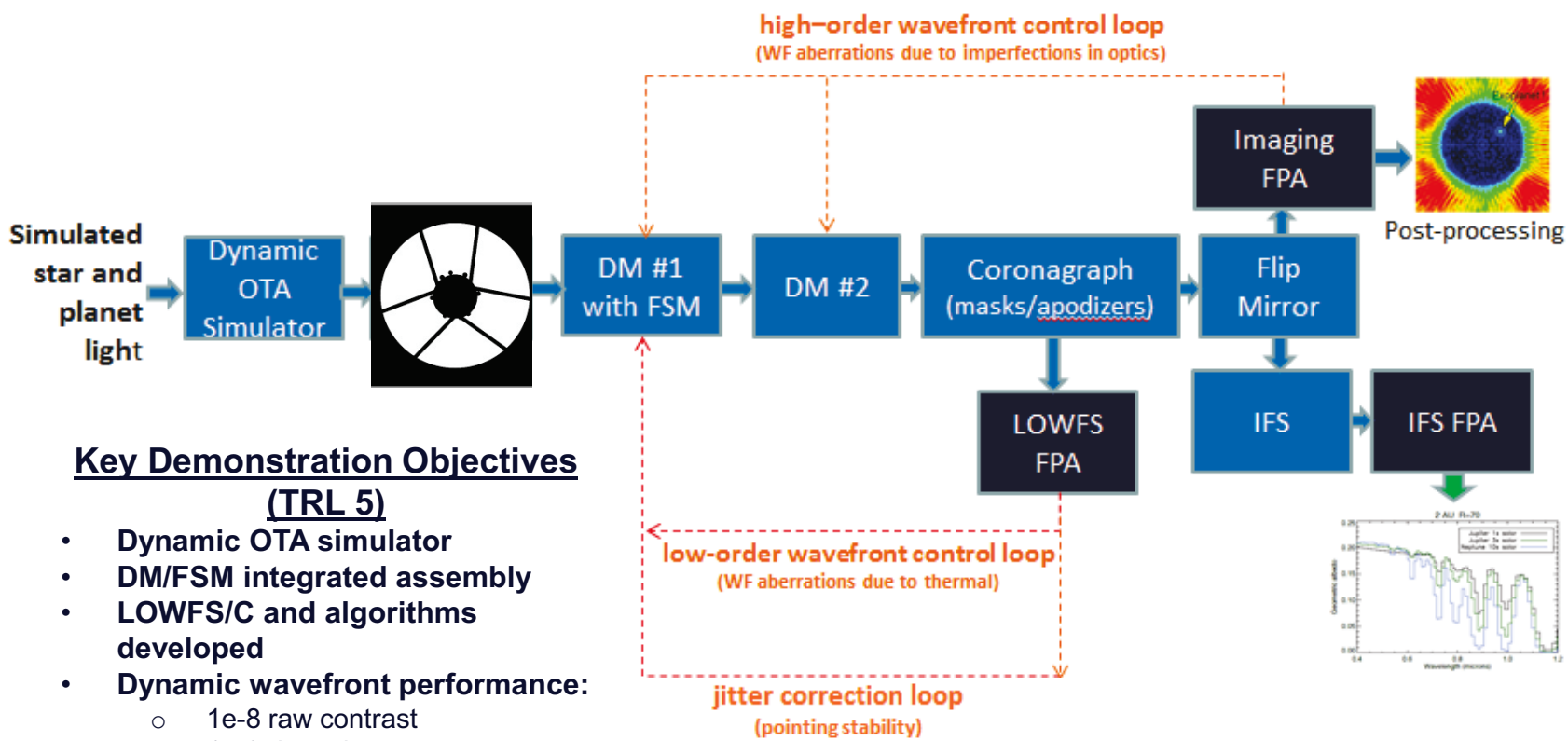
- **Coronagraph masks/apodizers for AFTA-WFIRST obscured pupil**
- **Two-DM configuration**
- **Wavefront control algorithms developed**
- **Static wavefront performance:**
  - 1e-8 contrast
  - 2% → 10% BW (in 500-600 nm window)



Dynamic Wavefront Systems-Level Testbed Demonstration

Possible Path to Closing Gap

Demonstrate dynamic wavefront performance in fully-assembled coronagraph vacuum testbed with simulated AFTA-WFIRST telescope pupil in a dynamic env't.



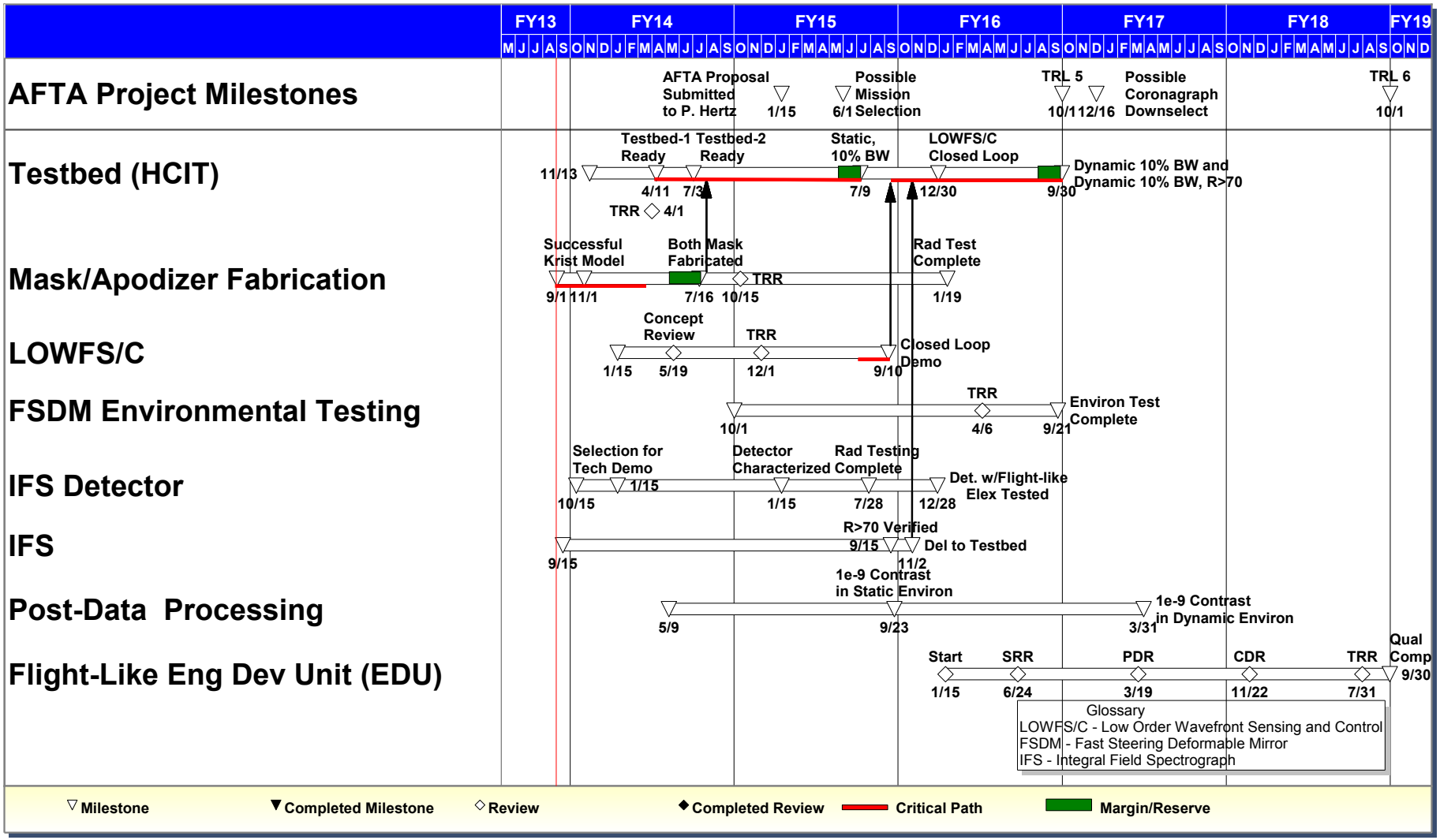
Key Demonstration Objectives (TRL 5)

- **Dynamic OTA simulator**
- **DM/FSM integrated assembly**
- **LOWFS/C and algorithms developed**
- **Dynamic wavefront performance:**
  - 1e-8 raw contrast
  - 1e-9 detection contrast
  - 2% → 10% BW (in 500-600 nm window)
  - IFS (R>70 TBD)
- **Planet simulation and extraction**

AFTA-WFIRST Coronagraph Tech Dev Top Level Schedule

Preliminary

Exoplanet Exploration Program



Acknowledgements

The work of PL and NS was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

© 2013. California Institute of Technology. Government sponsorship acknowledged.

Backup:
Detail of Starshade Technology Gaps

Starshade Technology Gaps (1/3)

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Capability Needed	Capability Today	Relative Gap	Relative Urgency
SG-1	Integration and Test: Verification & Validation	System Engineering	Develop an end-to-end plan for verification and validation, demonstrating that the design requirements can be met. No similar observatory has previously been flown.	Demonstrate analytically that the system requirements for the starshade and occulter can be verified and validated prior to flight.	It has been asserted that verification and validation of requirements will be accomplished through tests and model predictions.	H	H
SG-5	Control of Scattered Light: Sharp Edges to Minimize Solar Glint	Technology	Demonstrate with a baseline external occulter design that the brightness of sunlight scattered from the occulter would be less than the brightness of exozodiacal light.	Edge materials providing sunlight scatter < 22 mag/arcsec^2 and an empirical model of the scattering brightness. Effective edge width ~1µm	The use of baffle on the backside of the starshade should eliminate reflected sunlight from most petals. The designs of several edge shapes has been studied through optical modelling and tests in the lab. Preliminary work has been reported in the literature.	H	H

Importance:	H	Showstopper
	M	Major regret
	L	Not H or M
Urgency	H	Retire by 2015
	M	Retire by start Phase A (fy17)
	L	Retire by start of Phase B (fy19)

Starshade Technology Gaps (2/3)

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Capability Needed	Capability Today	Relative Gap	Relative Urgency
SG-3	Starshade Deployment	Technology	Demonstrate that an external occulter can be deployed repeatedly to within the budgeted tolerances.	Demonstrate that for a candidate deployment technology that the deviations of the petal base point from the design circle are repeatedly below the 3-sigma positioning requirement for a 10-9 contrast. Demonstrate this using a sufficient number of deployments to verify the requirements are met with 90% confidence.	Past deployment research establishes a defendable baseline for achievable accuracy: 1) AstroMesh radio-wavelength antennas have been deployed in space with up to 12-m aperture diameters and RMS *surface* accuracy of 1.4-mm; 2) JAXA deployed the KIKU-8 satellite with two 19m x 17m mesh reflector antennas with 2.4-mm *surface* accuracy.	M	H
SG-4	Validation of starshade optical models	Technology	Experimentally validate the equations that predict the contrast achievable with a starshade.	experimental validation of models of (a) diffracted intensity ~ 1e-11 accurate to ×/÷2, and (b) perturbation sensitivities accurate to 20% Make sure the test article is a good match to the flight	Experiments have validated optical diffraction models to a level of 4x10-10 in regions that are free of artifacts due to edge reflections. Additional effort is needed to validate models of wide-angle edge scattering.	M	M
SG-9	Thermal & Dynamic Stability: Mechanical Design and Solar Illumination	Technology	Demonstrate that a deployed shape can be controlled to within the budgeted tolerances for anticipated flight conditions of science operations.	Demonstrate that under the expected flight conditions that illumination of the starshade by the Sun will not cause thermal changes that will excede the allowable edge profile tolerances.	Further research is needed to better quantify the problem. It is currently perceived as a area of medium concern.	M	M

Starshade Technology Gaps (3/3)

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Capability Needed	Capability Today	Relative Gap	Relative Urgency
SG-7	Formation Sensing: Dedicated telescope	Technology	Demonstrate a sensor on the telescope that measures alignment of the starshade with the star within the budgeted alignment tolerances.	Sensitivity and stability of 0.1-0.5 m in lateral offset from collinearity	Possible shadow sensor experimental results from Printon or NGAS (TBC)	L	H
SG-10	Thermal & Dynamic Stability: Thrusters	Technology	High-Isp thrusters for long slew, with high durability and sufficent thrust. Thrusters for maintaining alignment during observations, with minimal plume stray light.	Thruster systems with Isp >~3000, thrust >~0.5 newton, and total mission Δv >7000 m/s. Maneuvering thrusters with brief pulses or low-scattering plume material	NEXT thruster, 2-3 units, represent the state of the art.	L	M
SG-6	Formation Flying GN&C: Between target stars	Technology	Demonstrate that the guidance, navigation and control algorithms of an external occulter can accomplish the slew from star to star.	Sensors and algorithms sufficient to guide a near-optimal trajectory across the sky, spanning 25 deg or more, and bring it to a stop within ~50 mas of collinearity. Sensor ability to distinguish the distant telescope from its background field stars.	Simulations have shown that the GN&C problem is tractable, although a flight demonstration of this application has not yet been done. Current devices and algorithms are probably easily adapted: Sensor with 50-70 mas accuracy; Legacy attitude control algorithms and short-range formation flying algorithms.	L	L
SG-2	Petal Manufacturing: Precision Edge Profile	Technology	Demonstrate that the profile of a single petal can be manufactured to the design tolerances.	Edge ripples and large-scale figure allow starlight diffraction at 1e-9 equivalent point source intensity, ideally at radius < petal tips.	A starshade petal was machined to edge tolerances that would enable contrasts of 3 x e-10 at the smallest inner working angle, if an entire starshade were made of such petals.	None	None

Backup:
Detail of AFTA Coronagraph Technology Gaps

AFTA Coronagraph Technology Gaps (1/3)

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Relative Gap	Relative Urgency
CG-1	Coronagraph Architecture has not been Designed or Fabricated for the AFTA Obscured Pupil	Technology	AFTA needs a coronagraph mask/architecture to suppress diffracted light from the OTA obscured pupil to meet contrast rqmt. To date, no mask/architectures have been demonstrated to achieve 1e-8 contrast with the AFTA obscured pupil.	H	H
CG-6	Coronagraph Performance with AFTA Pupil has not been Demonstrated at Breadboard Level	Technology (Validation Support)	Need a full system laboratory demonstration with simulated inflight AFTA wavefront perturbations and planet detection. At this time there is no system-level testbed.	H	H
CG-2	Low-Order Wavefront Sensing and Control not Demonstrated with Obscured Pupil	Technology	Current lab testing has only been done in a well-controlled stable lab env't. On-orbit low order WF variations (including pointing) may limit achieved contrast. We currently do not have a reliable estimate of telescope WF stability.	H?	H

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Capability Needed (extracted from AFTA STD Report)	Capability Today	Relative Gap	Relative Urgency
CG-7	Mature Flight Readiness of Deformable Mirror/Fast Steering Mirror	Technology (if MEMs) Engineering (if PMNs)	The AFTA coronagraph needs env't-tested deformable mirrors that have mirror qualities that can meet better than 10e-9 contrasts. To date, none of the deformable mirrors have completed full env't testing (in particular lifetime testing) and only one vendor has achieved better than 10e-8 contrast.	>= 48x48 actuators Lifecycled and environmentally tested Can enable raw contrasts of 1e-8 and stability to 1e-9 with obscured AFTA pupil.	64x64 actuators (Xinetics) Not lifecycled, partial env't testing (BMC and Xinetics) Correctability to raw contrast of 3e-10 with unobscured pupil (Xinetics); 1e-8 (BMC; monochromatic)	M	H
CG-3	Coronagraph Performance with Two Deformable Mirrors in Series not Demonstrated	Engineering	AFTA obscured pupil requires two deformable mirrors operating in series to provide required light suppression and symmetric dark hole. To date, this has never been done with an obscured pupil.	Circular dark hole demonstrated in vacuum testbed with obscured pupil.	Half-circular dark hole demonstrated in vacuum (HCIT) with one deformable mirror for an unobscured aperture (e-10 contrast) Symmetric dark hole demonstrated in air (Princeton) with two deformable mirrors for an unobscured aperture (1e-7 contrast)	M	M
CG-5	End-to-End Dynamic Modeling and Analyses of AFTA Coronagraph not Demonstrated	Engineering	At this time there is no end-to-end validated integrated opto-thermo-mechanical AFTA model. The engineering gap is: (1) currently limited knowledge of the OTA parameters (reflectivity, thermal stability, wavefront error, stiffness, etc) (2) limited validation of the STOP model.	The model must be good to within a factor of X TBD so that the science rqmts can still be met.	The optical tools are good to a factor of two using HCIT data. The thermal tools are good to a factor of Y.	M	M

Gap ID	Technology or Engineering Gap Title	Technology or Engineering Gap	Summary of Technology or Engineering Gap	Capability Needed (extracted from AFTA STD Report)	Capability Today	Relative Gap	Relative Urgency
CG-4	Post-Data Processing of Raw Contrast Performance Needed to Obtain 1e-9 Planet Detection	Technology	Expected coronagraph contrast capability with AFTA obscured pupil is 1e-8 and requires a 2% post-processing calibration. To date, about a 5-fold improvement has been achieved with an unobscured pupil.	>=50x planet detection threshold improvement at IWA 3 lambda/D with AFTA obscured pupil Planet simulator	~ 5x at IWA 4 lambda/D with unobscured pupil in HCIT No planet simulator	H	Z
CG-8	Spectrometer Pixel Cross Talk	Engineering	Spectral crosstalk rqmt for AFTA will require an intrascene contrast capability of around 1e-4. To date, ~1e-3 is achieved in existing IFS's.	~1e-4 intrascene contrast on a flight instrument.	~1e-3 intrascene contrast on ground-based telescopes.	M	Z
CG-9	Flight Readiness of Ultra-Low Noise IFS Detector is Low	Technology	AFTA needs a visible wavelength, extremely low noise detector behind the coronagraph spectrometer. To date, nearly noiseless (photon-counting) detectors have not been shown to meet their noise rqmts in a flight radiation environment.	Dark current noise < 1 e- 1000-10000 sec. Read noise < 1 e- for the sum of 100-1000 reads in a GEO radiation environment *These are very challenging rqmts; we need to confirm these rqmts are really needed.*	Silicon detectors can currently provide this low dark-current noise when cooled to ≈150K. Read noise < 1 e- ground testing (e2v EMCCDs) in a non-radiation environment 1kx1k	H	Z
CG-10	Coronagraph Performance has not been Demonstrated in a Flight-Like Thermal Environment	Engineering	To bridge the gap between breadboard and readiness to fabricate flight H/W, need a full system engineering unit that will undergo thermal and tandom vibe testing. There is no system-level engineering model.	Engineering model coronagraph built to flight-like design and ready to undergo limited environmental testing.	None	H	Z