Technology Development for Coronagraphic Imaging

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ExEP Program News
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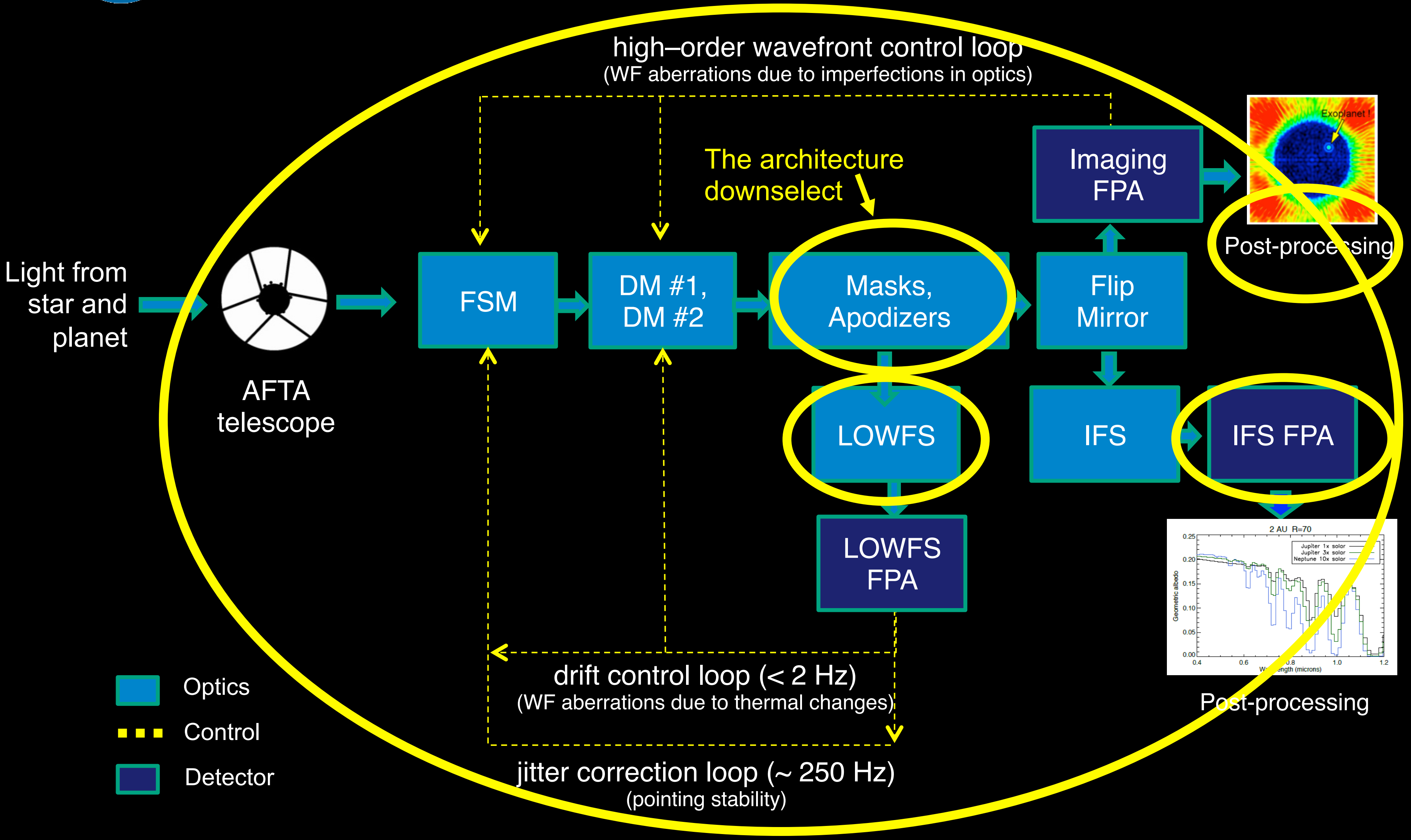
Block Diagram of a Typical Lyot Coronagraph



high–order wavefront control loop
(WF aberrations due to imperfections in optics)

The architecture downselect

Light from star and planet

AFTA telescope

FSM

DM #1, DM #2

Masks, Apodizers

Flip Mirror

Imaging FPA

LOWFS

LOWFS FPA

IFS

IFS FPA

Post-processing

Post-processing

drift control loop (< 2 Hz)
(WF aberrations due to thermal changes)

jitter correction loop (~ 250 Hz)
(pointing stability)

- 🟦 Optics
- ▪▪▪ Control
- ▪ Detector

Coronagraph Mask Fabrication

ID	Title	Description	Current Capability	Required Capability
CG-1	Architecture	Mask design and optical layout are needed that meet AFTA requirements	Three coronagraph technologies have obtained $\leq 10^{-8}$ raw contrast at 10% BW centered on 700 nm with an **unobscured** pupil.	One or more coronagraph technologies with $\leq 10^{-8}$ raw contrast at 10% BW filters from 430-980 nm with an **obscured** pupil

Possible Path to Closing Technology Gap

✓ **Selection process underway from six AFTA candidate coronagraph architectures to two.**
- Primary and backup

2. **Fabricate sets of each mask**

3. **Demonstrate performance in the two HCITs**
   - Mask/apodizer iterations likely

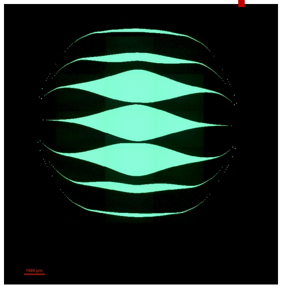
4. ✗ **Radiation testing (if necessary)**
   - Some of the masks may have dielectrics or liquid crystal polymers

5. **Down-selection to one architecture**

Before (unobscured pupil)

AFTA (obscured pupil)

Shaped Pupil Mask



Free standing transmissive binary silicon mask

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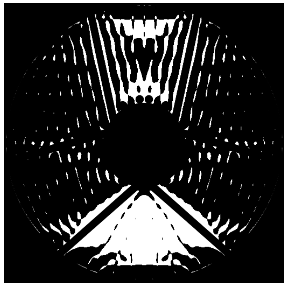
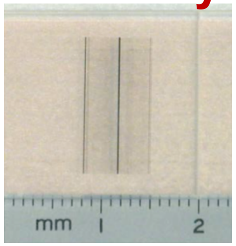


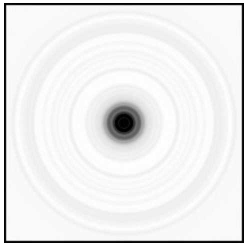
Black Si substrate with reflective patterned Al coating

Hybrid Lyot Mask



Linear mask with profiled Ni layer (amplitude) coated with profiled cryolite (phase)

→



Circular mask with profiled Ni layer (amplitude) coated with profiled MgF2 (phase)

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

ID	Title	Description	Current Capability	Required Capability
CG-2	Low-Order Wavefront Sensing & Control	Pointing stability and thermal drift	$\leq 10^{-9}$ raw contrast has only been achieved in a well-controlled **stable** lab environment and **unobscured pupil.**	Sufficient sensing and control of fast line-of-sight jitter and slow thermally-induced WFE to maintain closed-loop $\leq 10^{-8}$ raw contrast with an AFTA **obscured pupil** and simulated **dynamic flight environment**. Residual pointing stability expected to be ~0.4 mas for an expected AFTA on-orbit env't.

Possible Path to Closing Technology Gap

1. **Upon AFTA coronagraph selection and receiving telescope jitter and WF drift inputs, baseline LOWFS/C rqmts for each coronagraph.**
2. **Downselect from multiple LOWFS/C techniques.**
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 coronagraph testbed (HCIT)**

Knife Edged Mask
- 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

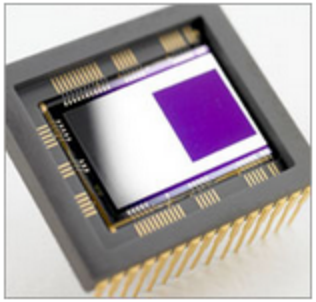
Fast WF Jitter
- PSF centroid or quad cell / pyramid APD for line of sigh at high rate
- WF tilt only

IFS Ultra-Low Noise Detector

ID	Title	Description	Current Capability	Required Capability
CG-9	Ultra-Low Noise Visible Detector	Low-noise detector needed to characterize exoplanet spectra	Si detector cooled to 150K can achieve dark current < 0.0001 e/pix/s. 1kx1k EM CCDs provide < 0.1 e/pix RN with standard electronics in a non-radiation environment.	Dark current < 0.0001 e/pix/s and read noise < 0.1 e/pix built with flight electronics in GEO radiation flight environment. 2kx2k format (TBD)

Possible Path to Closing Technology 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**
3. **Select and acquire a baseline detector; characterize under realistic operational scenarios**
   - Includes low-noise electronics
4. **Perform radiation testing of the selected detector; before and after characterization.**
5. **Investigate flight read-out electronics design.**
6. **Design, build, and test flight-like electronics boards.**



e2V Electron Multiplying CCD
(a candidate device)

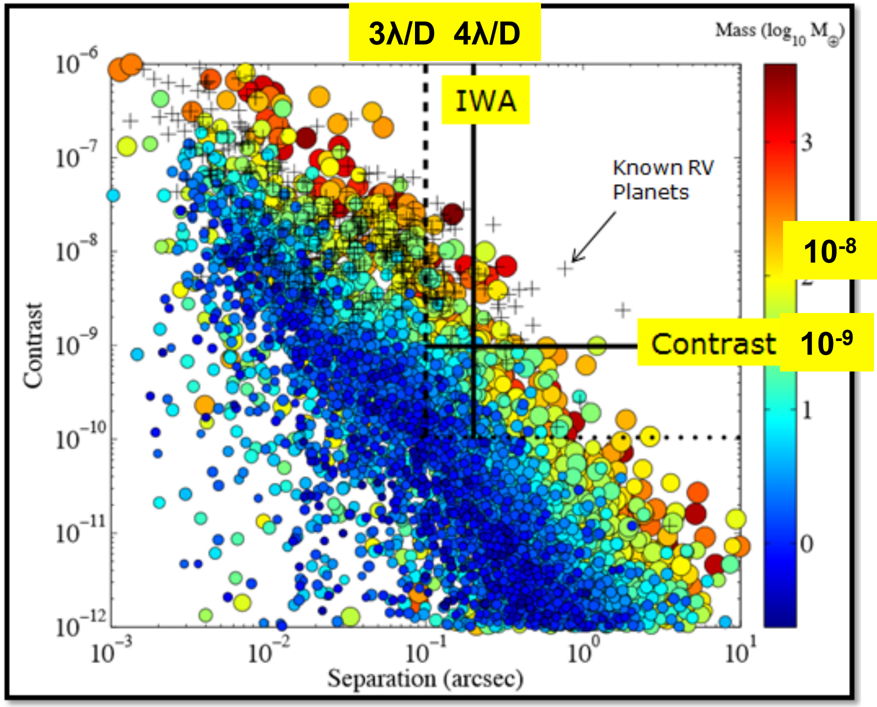
ESA successfully demonstrated gain stability and radiation tolerance for EMCCDs.

Post-Data Processing

ID	Title	Description	Current Capability	Required Capability
CG-4	Data Architecture Post-Processing	Software algorithms are needed to improve detectability of planets in data dominated by speckle noise	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 1e-4 to 1e-7, dominated by phase errors only.	A 10-fold contrast improvement in the visible from 1e-8, where amplitude errors are expected to be important.

Possible Path to Closing Technology Gap

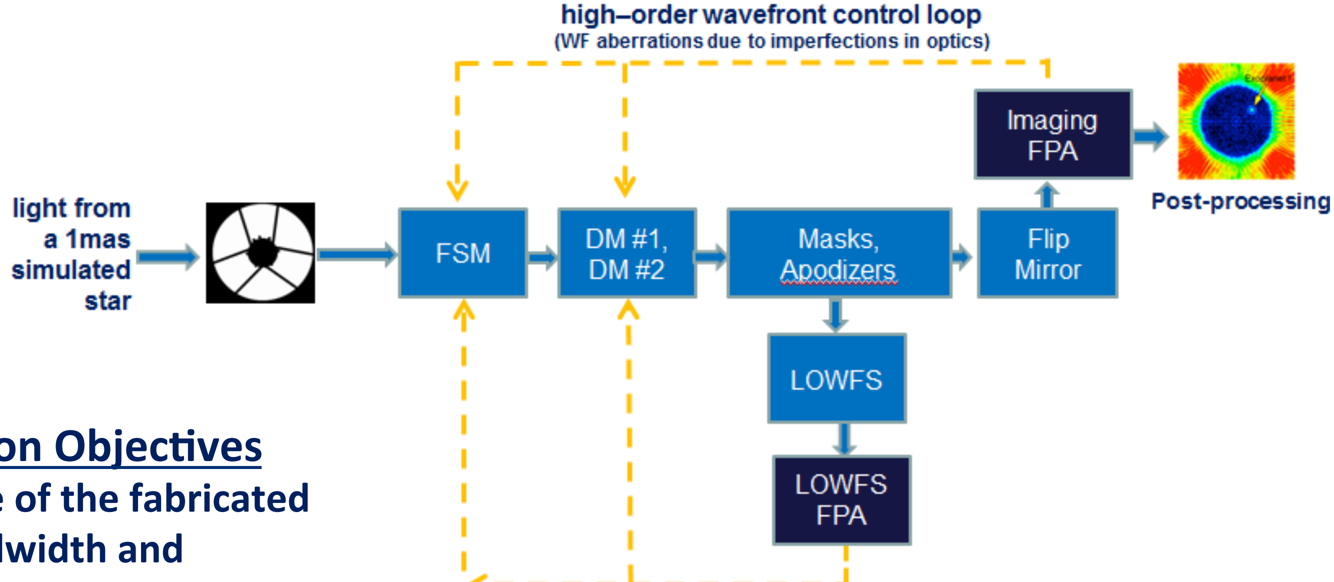
1. **Assess the performance of current state-of-the-art post-processing algorithms using existing HCIT data and simulated multiwavelength IFS data**
   a) evaluate the regime where contrast in no longer dominated by phase errors.
2. **Understand telescope/instrument temporal behavior and assess possible 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)

System-Level Testbed Demonstration with Dynamic Wavefront

ID	Title	Description	Current Capability	Required Capability
CG-6	Breadboard Demo	High-fidelity laboratory contrast demonstrations	Testing with a simulated star in vacuum with **semi-static wavefront errors** and **unobscured** pupil at 10% BW at **700 nm**.	Testing with a simulated star and **telescope simulator** in vacuum with **dynamic wavefront errors** and **obscured** pupil at 10% BW at **430-980 nm**.



high–order wavefront control loop
(WF aberrations due to imperfections in optics)

light from a 1mas simulated star

FSM

DM #1, DM #2

Masks, Apodizers

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LOWFS FPA

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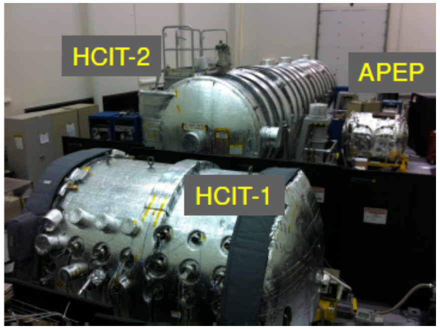
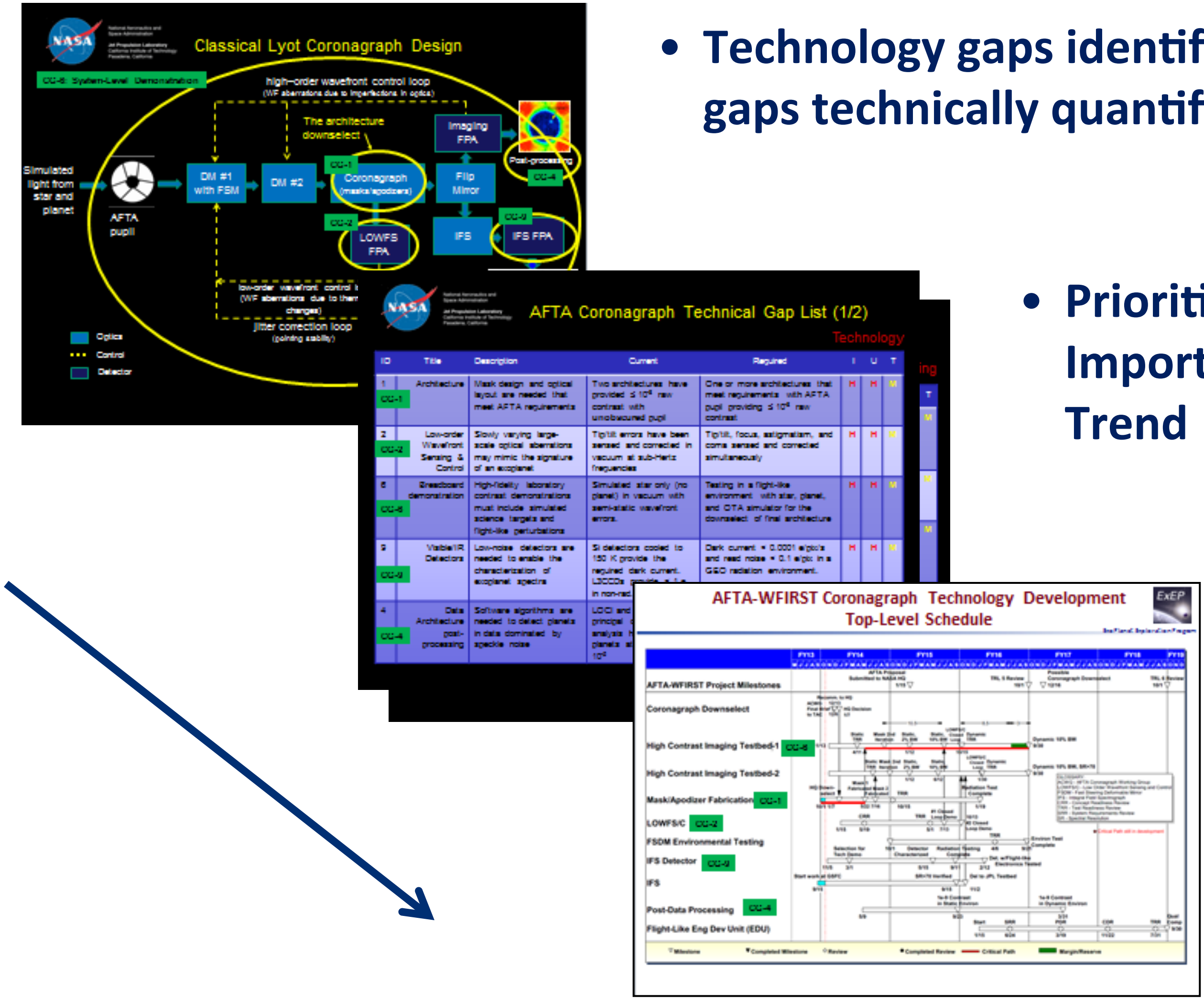


Key Demonstration Objectives

- Contrast performance of the fabricated masks, including bandwidth and throughput
- LOWFS/C subsystem and nulling algorithms
- Preliminary speckle reduction algorithms
- WFE sensitivity studies
- Optical modeling validation

ExEP Technology Development Process



AFTA Coronagraph Technical Gap List (1/2)

Technology

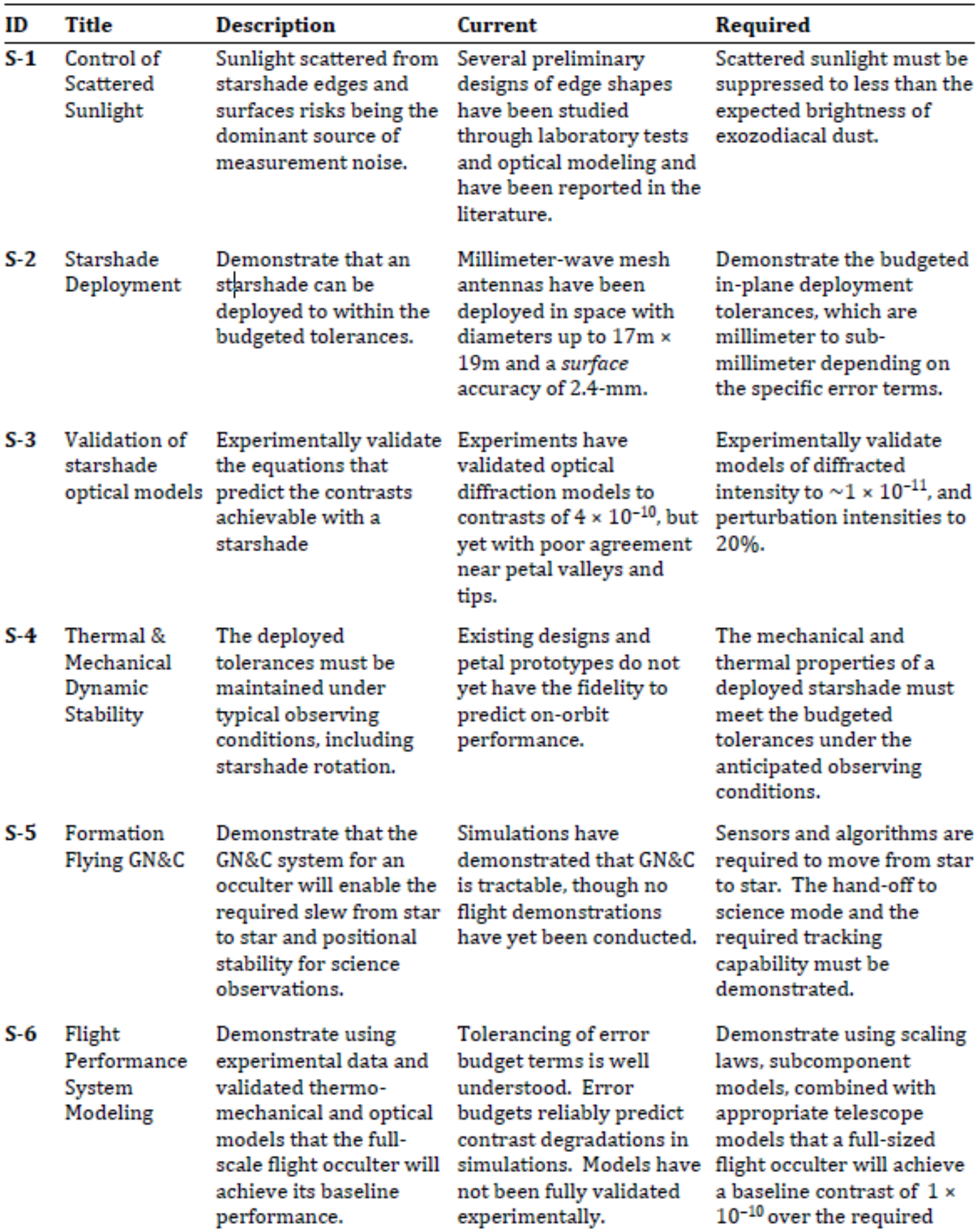
ID	Title	Description	Current	Required	I	U	T
1 CG-1	Architecture	Mask design and optical layout are needed that meet AFTA requirements	Two architectures have provided ≤ 10^{8} raw contrast with unobscured pupil	One or more architectures that meet requirements with AFTA pupil providing ≤ 10^{8} raw contrast	H	H	M
2 CG-2	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet	Tip/tilt errors have been sensed and corrected in vacuum at sub-Hertz frequencies	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously	H	H	M
6 CG-6	Breadboard demonstration	High-fidelity laboratory contrast demonstrations must include simulated science targets and flight-like perturbations	Simulated star only (no planet) in vacuum with semi-static wavefront errors.	Testing in a flight-like environment with star, planet, and OTA simulator for the downselect of final architecture	H	H	M
9 CG-9	Visible/IR Detectors	Low-noise detectors are needed to enable the characterization of exoplanet spectra	Si detectors cooled to 150 K provide the required dark current. L3CCDs provide in non-rad.	Dark current < 0.0001 e/pix/s and read noise < 0.1 e/pix in a GEO radiation environment.	H	H	M
4 CG-4	Data Architecture post-processing	Software algorithms are needed to detect planets in data dominated by speckle noise	LOCI and principal analysis planets 10^{8}				

AFTA-WFIRST Coronagraph Technology Development
Top-Level Schedule

- Technology gaps identified and described, gaps technically quantified
- Prioritized for relative Importance, Urgency, and Trend
- Plans created to retire the top priorities in time

Coronagraph technology plans for AFTA far along; starshade next.

Starshade Technology Development Areas



ID	Title	Description	Current	Required
S-1	Control of Scattered Sunlight	Sunlight scattered from starshade edges and surfaces risks being the dominant source of measurement noise.	Several preliminary designs of edge shapes have been studied through laboratory tests and optical modeling and have been reported in the literature.	Scattered sunlight must be suppressed to less than the expected brightness of exozodiacal dust.
S-2	Starshade Deployment	Demonstrate that an starshade can be deployed to within the budgeted tolerances.	Millimeter-wave mesh antennas have been deployed in space with diameters up to 17m × 19m and a *surface* accuracy of 2.4-mm.	Demonstrate the budgeted in-plane deployment tolerances, which are millimeter to sub-millimeter depending on the specific error terms.
S-3	Validation of starshade optical models	Experimentally validate the equations that predict the contrasts achievable with a starshade	Experiments have validated optical diffraction models to contrasts of 4×10^{-10}, but yet with poor agreement near petal valleys and tips.	Experimentally validate models of diffracted intensity to $\sim 1 \times 10^{-11}$, and perturbation intensities to 20%.
S-4	Thermal & Mechanical Dynamic Stability	The deployed tolerances must be maintained under typical observing conditions, including starshade rotation.	Existing designs and petal prototypes do not yet have the fidelity to predict on-orbit performance.	The mechanical and thermal properties of a deployed starshade must meet the budgeted tolerances under the anticipated observing conditions.
S-5	Formation Flying GN&C	Demonstrate that the GN&C system for an occulter will enable the required slew from star to star and positional stability for science observations.	Simulations have demonstrated that GN&C is tractable, though no flight demonstrations have yet been conducted.	Sensors and algorithms are required to move from star to star. The hand-off to science mode and the required tracking capability must be demonstrated.
S-6	Flight Performance System Modeling	Demonstrate using experimental data and validated thermo-mechanical and optical models that the full-scale flight occulter will achieve its baseline performance.	Tolerancing of error budget terms is well understood. Error budgets reliably predict contrast degradations in simulations. Models have not been fully validated experimentally.	Demonstrate using scaling laws, subcomponent models, combined with appropriate telescope models that a full-sized flight occulter will achieve a baseline contrast of 1×10^{-10} over the required

Funding Sources

ExEP
TDEM 12 ← ***Suzanne Casement/NGAS***
Starshade Straylight Mitigation through Edge Scatter Modeling and Sharp-Edge Materials Development

TDEM 10

ExEP
TDEM 12 ← ***Tiffany Glassman/NGAS***
Demonstration of Starshade Starlight-Suppression Performance in the Field

STDT
ExEP

Note: one TDEM 09 mitigated risk of petal fabrication.

Lawson, AAS poster, 01/14