ExEP Technology Needs and Status

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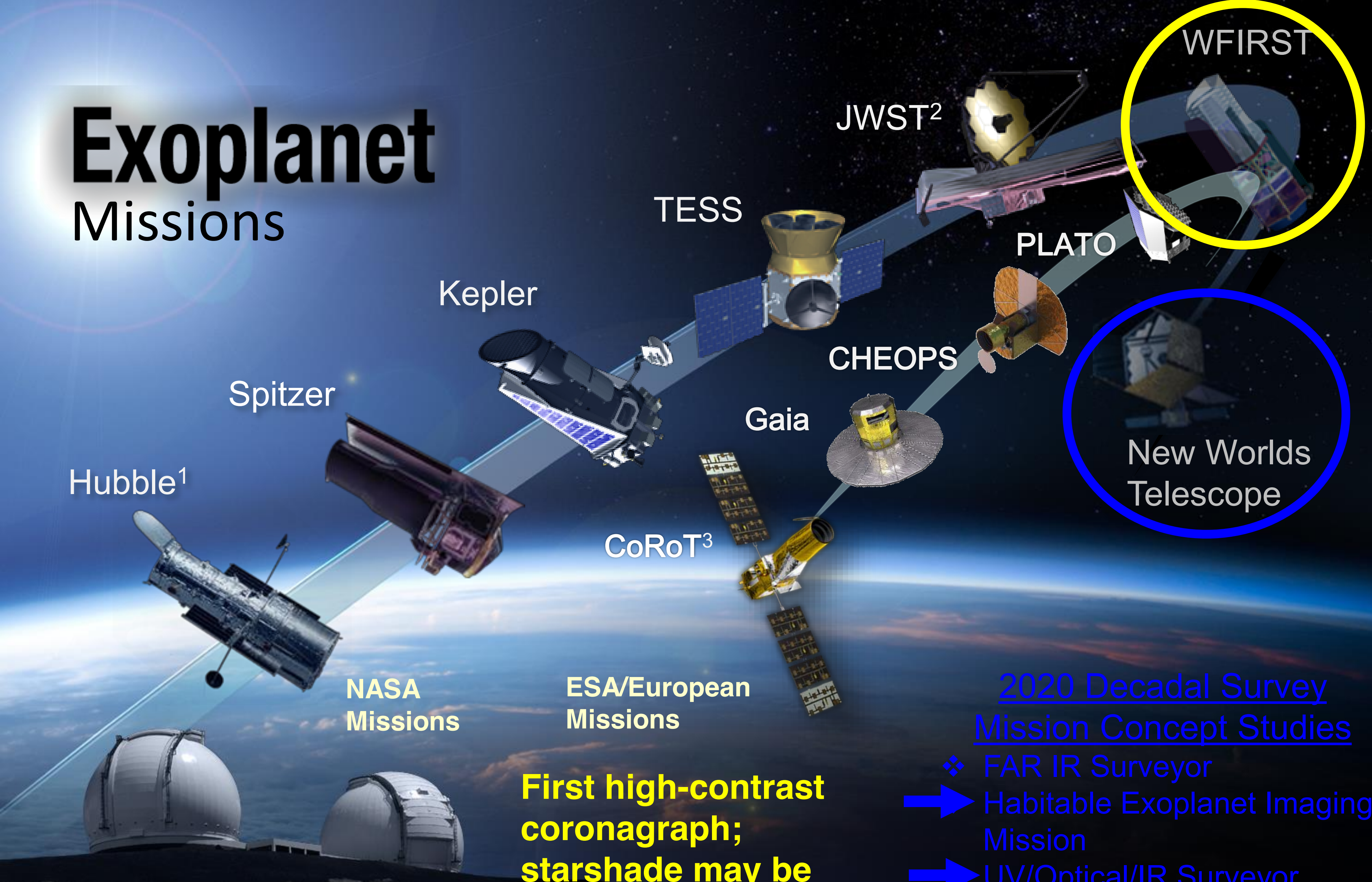
01/04/16
ExoPAG Meeting
2016 Kissimmee, FL

CL#15-5804

Exoplanet Missions



First high-contrast coronagraph; starshade may be studied

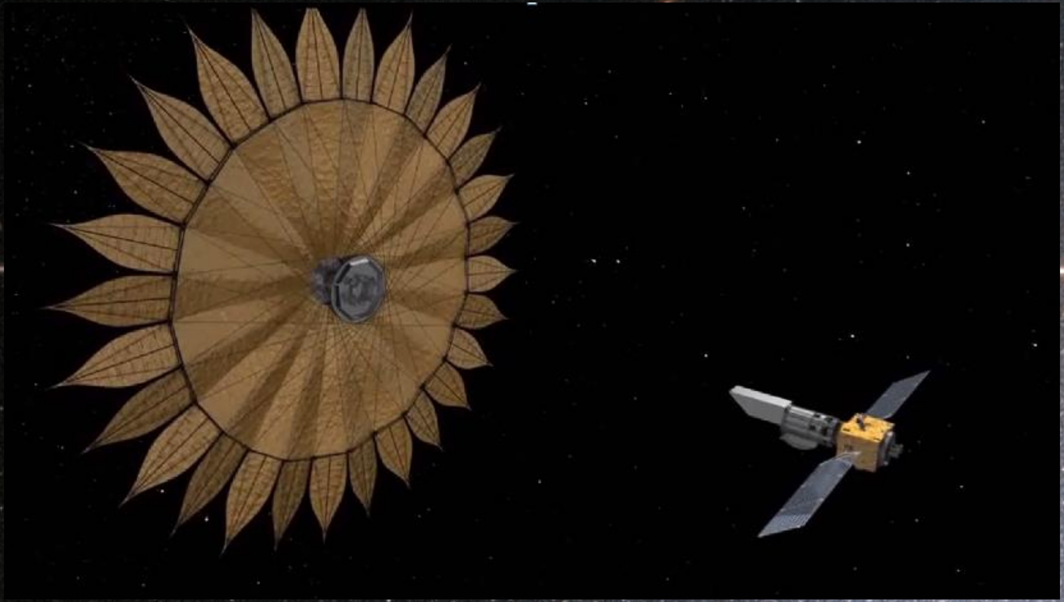
2020 Decadal Survey Mission Concept Studies

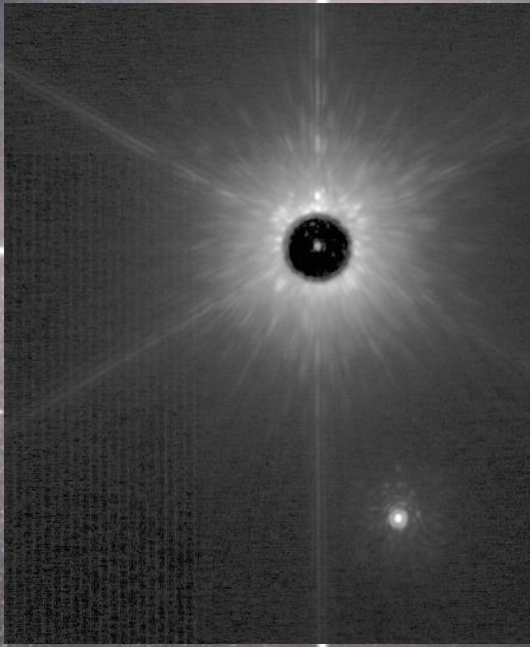
- ❖ FAR IR Surveyor
- ➡ Habitable Exoplanet Imaging Mission
- ➡ UV/Optical/IR Surveyor
- ❖ X-ray Surveyor

[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership
[3] CNES/ESA Partnership

Enabling Starlight Suppression Technologies

External Occulters (Starshades)

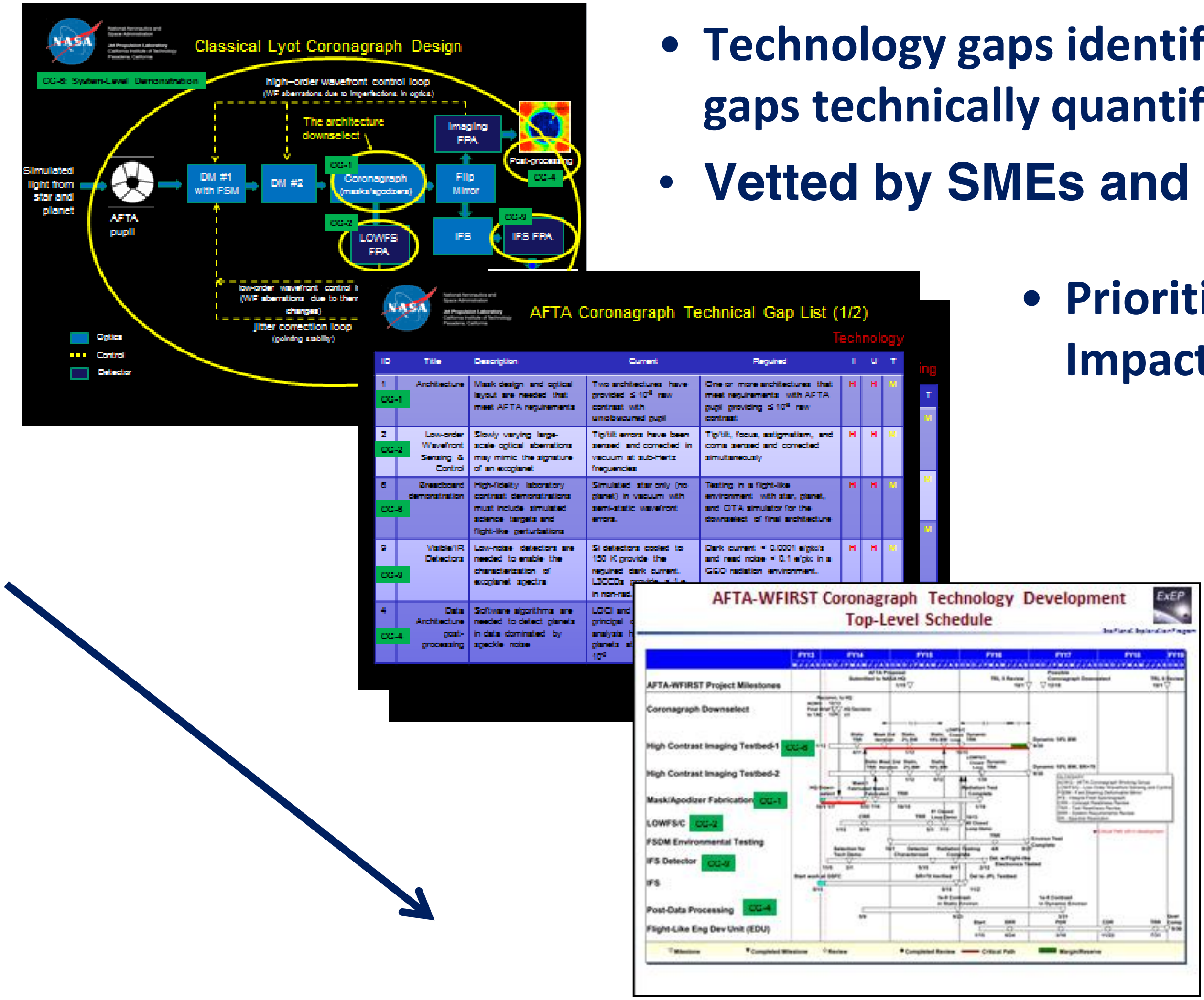




Nulling Interferometry

Internal Occulters (Coronagraphs)

ExEP Technology Development Process



AFTA Coronagraph Technical Gap List (1/2)

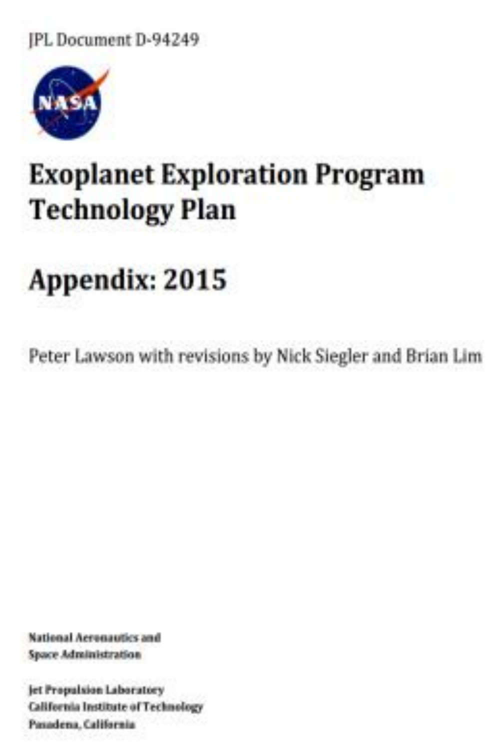
Technology

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 c... analysis h... planets a... 10^8				

AFTA-WFIRST Coronagraph Technology Development
Top-Level Schedule

- **Technology gaps identified and described, gaps technically quantified**
- **Vetted by SMEs and ExoPAG**
- **Prioritized for relative Impact, Urgency, and Trend**
- **Plans created to retire the top priorities in time**
- **Possible funding sources:**
  - TDEM
  - ExEP
  - SBIR
  - Center IR&D
  - Industry

ExEP Technology Gap Lists



JPL Document D-94249

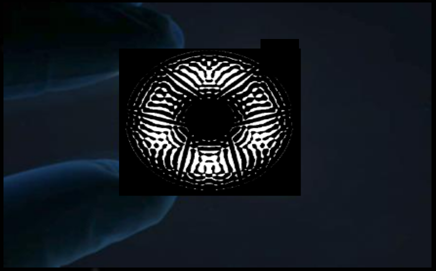
Exoplanet Exploration Program Technology Plan

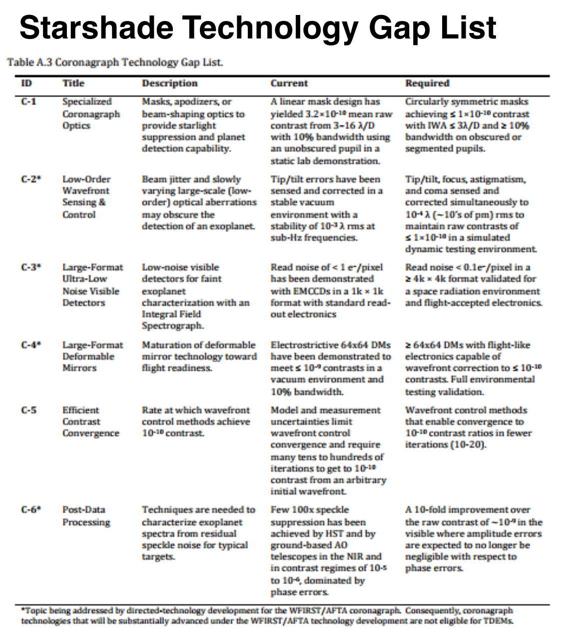
Appendix: 2015

Peter Lawson with revisions by Nick Siegler and Brian Lim

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



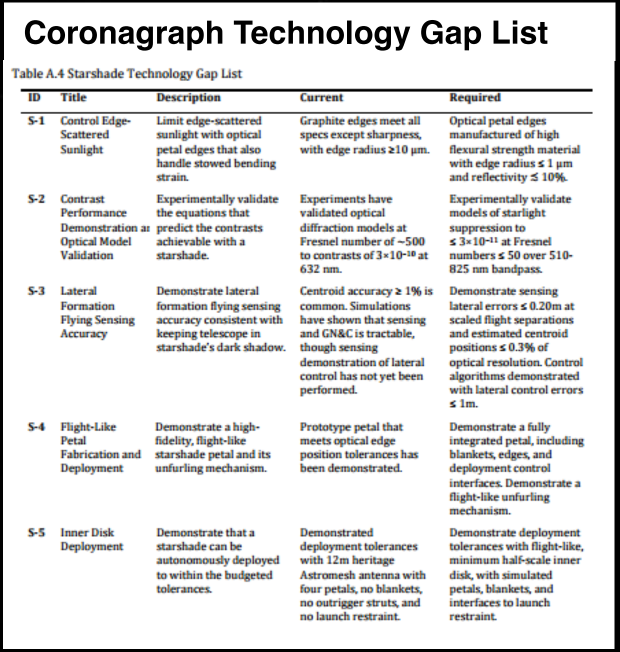


Starshade Technology Gap List

Table A.3 Coronagraph Technology Gap List.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving $\leq 1\times10^{-10}$ contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10's of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e^-/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics	Read noise < 0.1e^-/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-5} to 10^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-9} in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.



Coronagraph Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≲ 10%.
S-2	Contrast Performance Demonstration ai Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally validate models of starlight suppression to $\leq 3\times10^{-11}$ at Fresnel numbers ≤ 50 over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Next update by Jan 2016

http://exep.jpl.nasa.gov/technology/

Today

A. Please listen for:

1. Completeness – Are there any gaps missing?

2. Correctness – Are the “Desired Needs” the right ones?

B. I’ll also provide status on the various technologies and possible paths forward

<u>Assumptions:</u>

- **The technology needs are based on satisfying the following science goal**
  - ***Detection and spectral characterization of exo-earths***
  - Other science capabilities is assumed to come for free

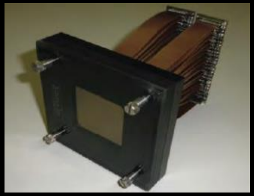
- **All the technology gaps selected are “enabling” technologies**
  - None are purely “enhancing”

- **The technology gaps are in priority order…**
  - … but because they’re all enabling their order is less relevant

Coronagraph Technology Needs

Contrast


Coronagraph architectures


Deformable mirrors

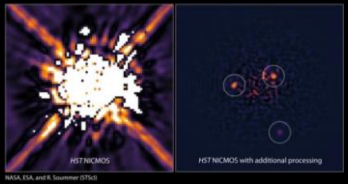
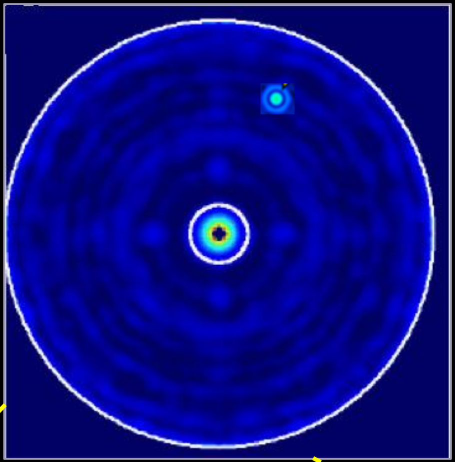
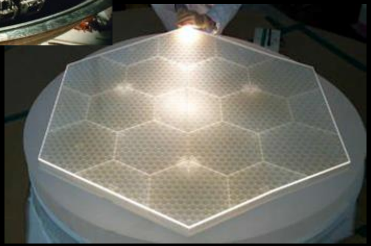


Image post-processing

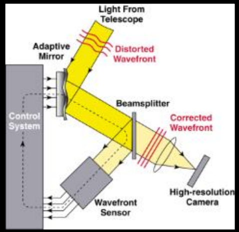


Angular Resolution


Large monolith


Segmented

Contrast Stability



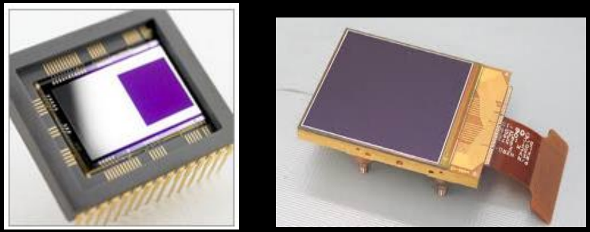
Low-order wavefront control

5


Segment phasing and rigid body control

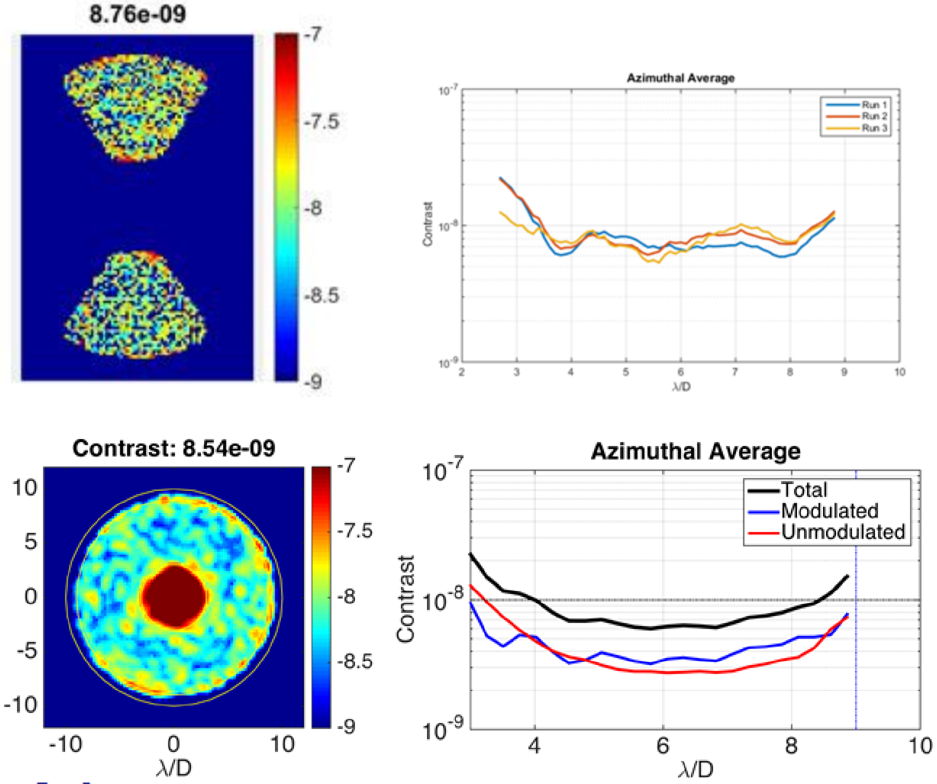

Telescope vibration control

Detection Sensitivity


Ultra-low noise detectors
(visible and infrared wavelengths)

Coronagraph Architecture

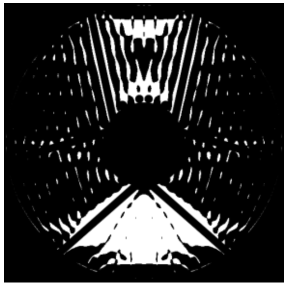
Description	Current Capabilities	Desired Capabilities
Coronagraph optics and architecture that suppress diffracted starlight by a factor of ≤ 10^{-9} at visible and infrared wavelengths.	3×10^{-10} raw contrast at 10% bandwidth across angles of 3-16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vac lab env't (Hybrid Lyot) 9×10^{-9} raw contrast at 10% bandwidth across angles of 4-11 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab env't (WFIRST)	Circularly symmetric masks achieving ≤ 10^{-10} contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured and/or segmented pupils in a simulated dynamic vacuum environment.



Recent Activities

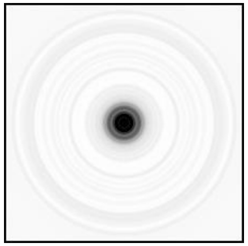
Both WFIRST coronagraph masks have achieved < 10^{-8} raw contrast at across a 3-9 λ/D symmetric dark hole with obscured pupil.

Shaped Pupil Mask



Black Si substrate with reflective patterned Al coating

Hybrid Lyot Mask



Circular mask with profiled Ni layer coated with patterned PMGI dielectric

Coronagraph Architecture

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Next Steps to Closing Technology Gap

1. First demonstration of < 10^{-8} coronagraph performance with an obscured pupil in a simulated dynamic environment. (WFIRST; Sept 2016)
2. First demonstrations of the PIAA CMC (WFIRST; CY16)
3. ExEP Starshade Coronagraph Design & Analysis (SCDA) effort (FY16)
4. Demonstrations of next generation coronagraphs at STScI, NASA-GSFC, and the ExEP HCIT (FY16-FY19)

Recent Activities

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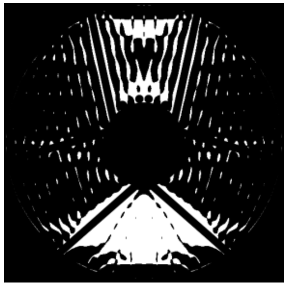
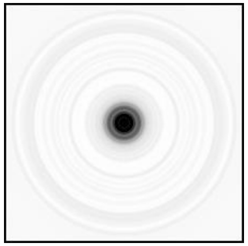
Shaped Pupil Mask



Black Si substrate with reflective patterned Al coating

Hybrid Lyot Mask



Circular mask with profiled Ni layer coated with patterned PMGI dielectric

WFIRST Contrast and IWA Results to Date

Hybrid Lyot Coronagraph

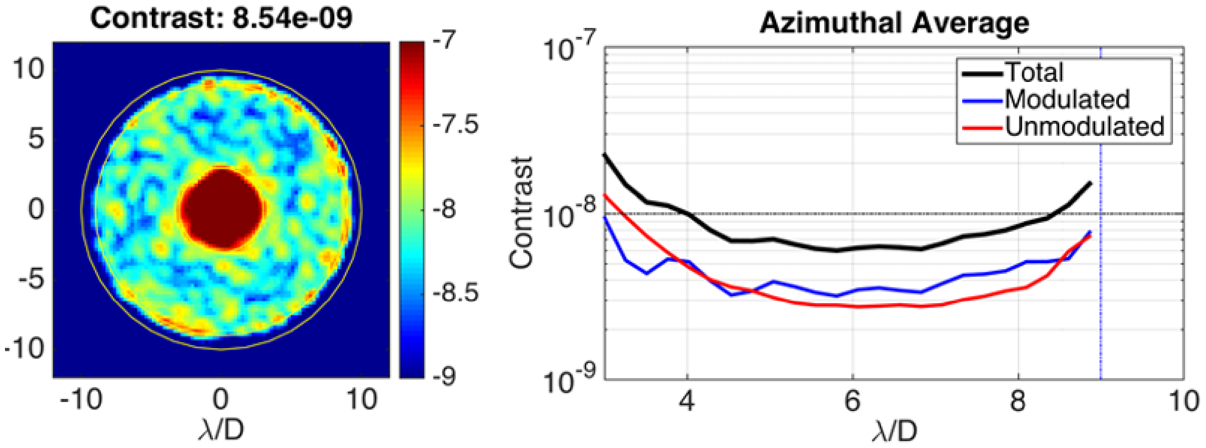


Figure 8: Hybrid Lyot coronagraph 10% broadband centered at 550 nm with mean contrast of 8.5x10^{-9} across a 3-9 λ/D dark hole (WFIRST; Milestone #5). Data collected from HCIT-2 at JPL. The 10% bandwidth was achieved using five 2% bands averaged; calibration uncertainty is ±2%. Mask was fabricated by e-beam lithography at JPL's Microdevices Laboratory.

Shaped Pupil Coronagraph

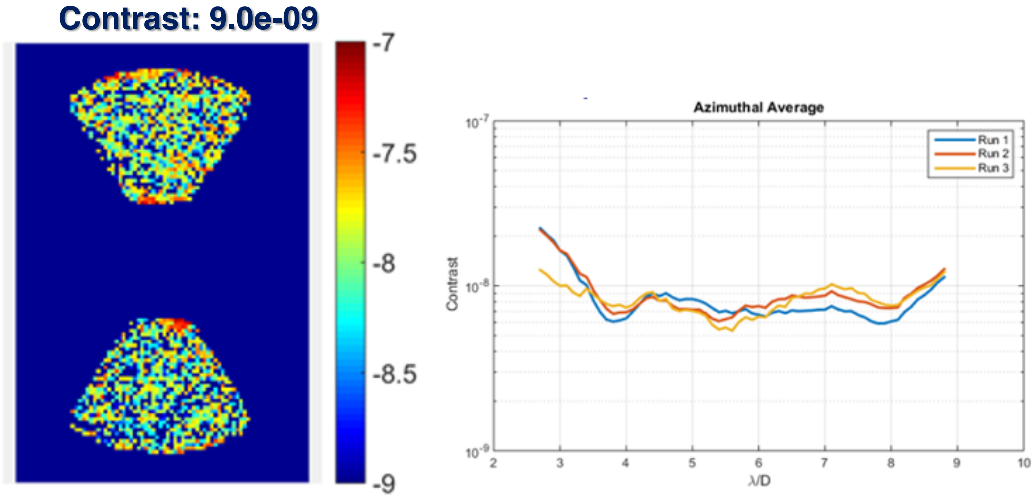


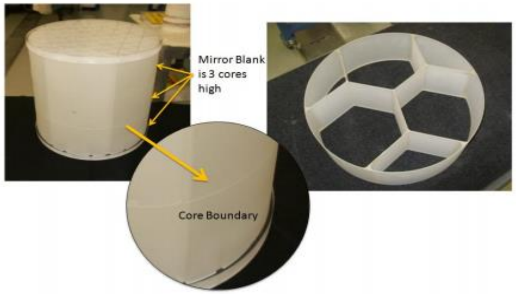
Figure 11: Shaped Pupil coronagraph 10% broadband centered at 550 nm with mean contrast of 9x10^{-9} across a 3-9 λ/D two-sided 65° wedge dark hole (WFIRST; Milestone #5). Data collected from HCIT-1 at JPL. The 10% bandwidth was achieved using five 2% bands.

Large Aperture Primary Mirrors - Monoliths

Current Capabilities	Desired Capabilities
Monolith: 3.5m sintered SiC with < 3 um SFE (Herschel) 2.4m ULE with ~ 10 nm SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1. **Segmented:** 6.5m Be with 25 nm SFE (JWST) Non-NASA: 6 dof, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm over 4 hr with thermal control	Aperture: 4m - 12m; SFE < 10 nm RMS (wavelength coverage 400 nm - 5000 nm) Wavefront stability better than 10 pm RMS per wavefront control step. Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Environmentally tested.

Possible Next Steps to Closing Technology Gap

- AMTD Phase 2 is currently building a 1.5 meter, 200 mm thick sub-scale model of a 4m ULE mirror to demonstrate lateral scalability of the stacked core process. (FY16-FY17)
- When complete, AMTD-2 plans to characterize its static thermal wavefront error deformation.
- AMTD Phase 2 is currently polishing a 1.2m Zerodur mirror for the purpose of thermal wavefront error characterization. (CY16)
- HabEx will study range of monolith architectures (CY16-17)

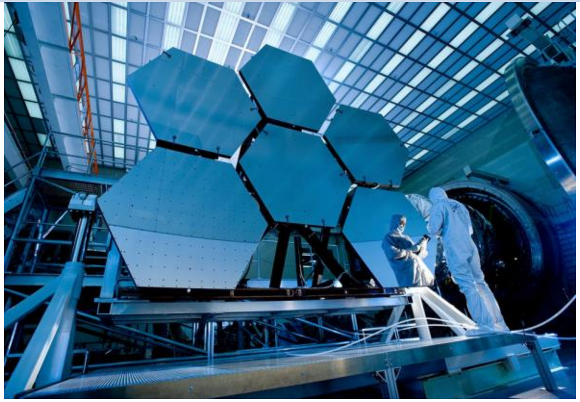


Recent Activities

- Advanced Mirror Technology Development (AMTD) project (PI Stahl) produced a 43 cm diameter cut-out of a 4m, 40 cm thick mirror ULE using a new five-layer stack and fuse process (5.5 nm rms)
- Preliminary study conducted by MSFC of 4m monolith on SLS (Block 1)

Large Aperture Primary Mirrors - Segmented

Current Capabilities	Desired Capabilities
Monolith: 3.5m sintered SiC with < 3 um SFE (Herschel) 2.4m ULE with ~ 10 nm SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1. **Segmented:** 6.5m Be with 25 nm SFE (JWST) Non-NASA: 6 dof, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm over 4 hr with thermal control	Aperture: 4m - 12m; SFE < 10 nm RMS (wavelength coverage 400 nm - 5000 nm) Wavefront stability better than 10 pm RMS per wavefront control step. Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Environmentally tested.



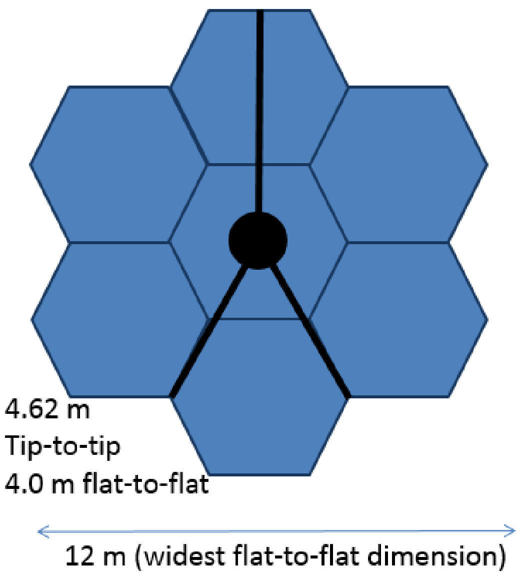
JWST at MSFC's XRCF

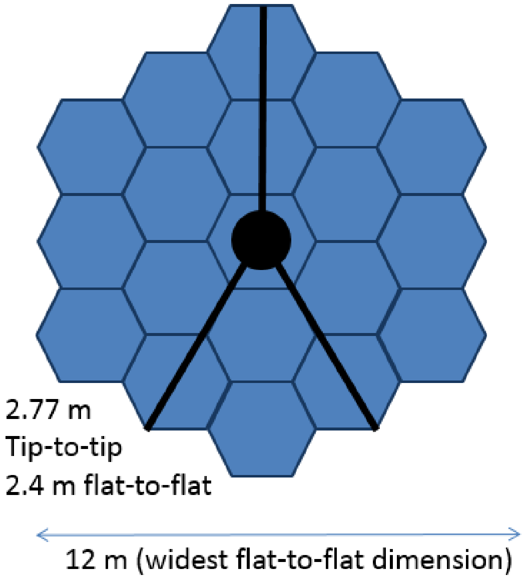
Recent Activities

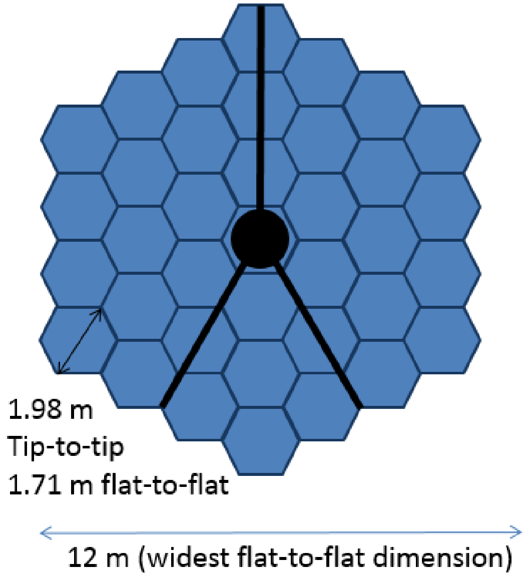
- **ATLAST wraps up after several years of design work.**
- **ExEP SCDA effort begun**
  - selection of 5 coronagraph architectures
  - creation of a reference aperture team.

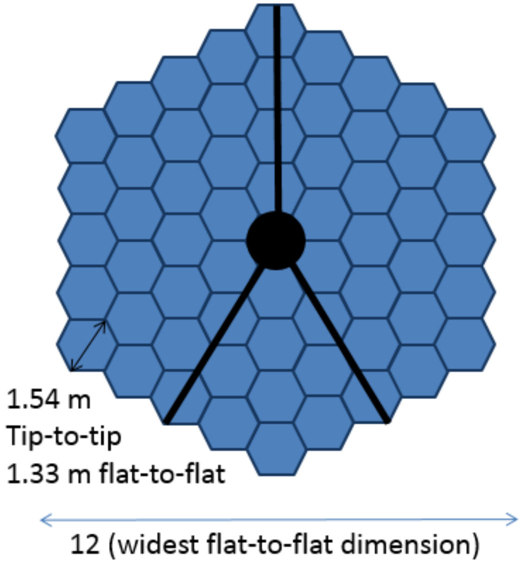
Reference Apertures Under Consideration in the SCDA Effort

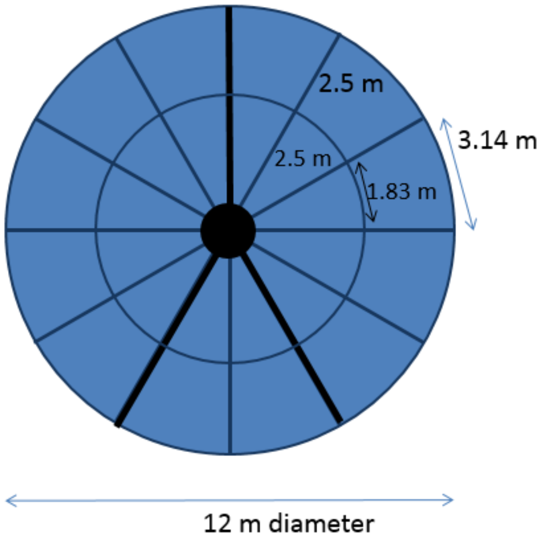
Exoplanet Exploration Program

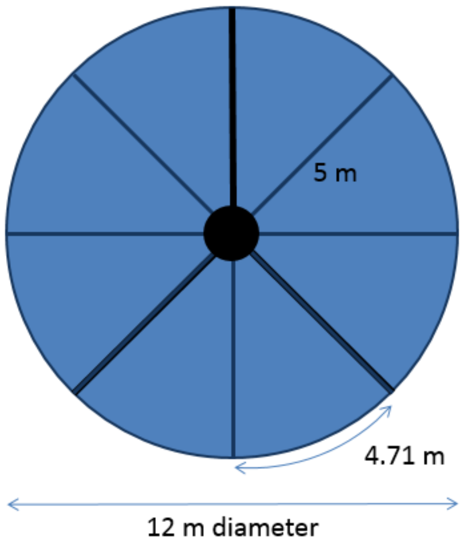












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JWST at MSFC XRCF

Possible Next Steps to Closing Technology Gap

- SCDA effort will identify which coronagraph architectures meet exo-earth imaging requirements on a segmented telescope (CY16).
- LUVOIR concept study will define the architecture, materials, and operating wavelength range for a segmented telescope. (CY16-17)
- Possible 2nd year added for SCDA adding dynamic disturbances and rigid-body segment errors (FY17)

Recent Activities

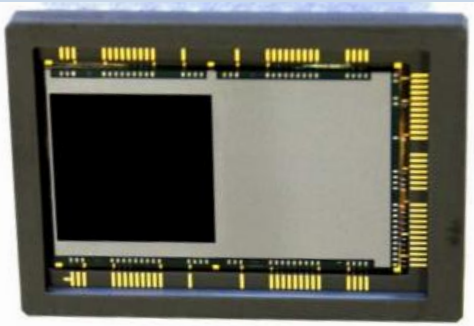
- ATLAST wraps up after several years of design work.
- ExEP SCDA effort begun
  - selection of 5 coronagraph architectures
  - creation of a reference aperture team.

Ultra-Low Noise Visible Detector

Description	Current Capabilities	Desired Capabilities
Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph	1kx1k silicon EMCCD detectors provide dark current of 8×10^{-4} e-/px/sec; effective read noise <0.2 e- rms (in EM mode) after irradiation when cooled to 165.15K. 4kx4k EMCCD fabricated but still under development.	Effective read noise <0.1e- rms; CIC < 3×10^{-3} e-/px/fram; dark current < 10^{-4} e-/px/sec tolerant to a space radiation environment over mission lifetime. ≥ 2kx2k format

Possible Next Steps to Closing Technology Gap

1. **Conclude post-radiation performance assessment of the 1kx1k EMCCD (WFIRST; CY16)**
   - ☐ Incorporate effect of radiation damaged induced traps in the detector model to predict planet yield at end of life.
2. **LUVOIR and HabEx concept studies will define needed requirements.**
   - ☐ **EEMCCD plan needed to likely exceed WFIRST results**
3. **Follow progress of e2V 4kx4k demonstrations**
   - ☐ Radiation test if/when performance requirements are met



Recent Activities

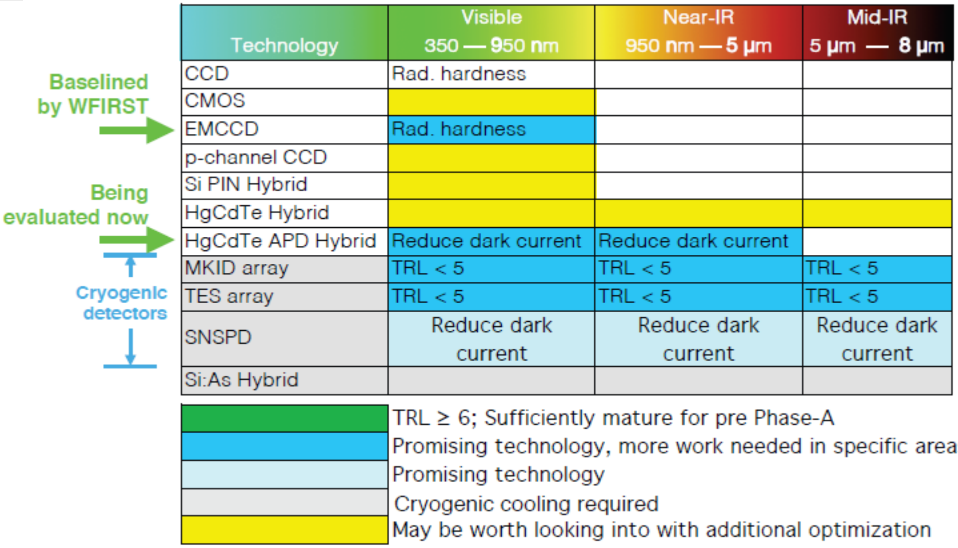
- **e2v EM CCD201-20 baselined for the WFIRST; characterized using a NüVü EM N2 camera**
  - ❖ meets the WFIRST beginning of life performance requirements
  - ❖ RN, dark current, CIC results all appear favorable
- **Chip underwent radiation testing**

Ultra-Low Noise Infrared Detector

Description	Current Capabilities	Desired Capabilities
Near infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-earth spectral characterization with Integral Field Spectrographs.	HgCdTe photodiode arrays have read noise <~ 2 e- rms with multiple non-destructive reads; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST). HgCdTe APDs have dark current ~ 10-20 e-/s/pix, RN << 1 e- rms, and < 1kx1k format Cryogenic (superconducting) detectors have essentially no read noise nor dark current; radiation tolerance is unknown.	Read noise << 1 e- rms, dark current < 0.001 e-/pix/s, in a space radiation environment over mission lifetime. ≥ 2kx2k format

Possible Next Steps to Closing Technology Gap

1. HabEx and LUVOIR mission concept studies will define the operating wavelength range (CY16); IR detectors may rise in urgency
   - ☐ Plan needed to advance IR detector technology
2. Determine limiting noise sources in HgCdTe arrays from JWST and WFIRST arrays (CY16-17)
3. Review the results of HgCdTe APD usage on ground-based AO systems (CY16-17)
4. MKID array being delivered to SCExAO on Subaru telescope in CY17; PICTURE-C CY19
5. Possible TES advancement at GSFC (CY16-18)



Technology	Visible 350 — 950 nm	Near-IR 950 nm — 5 μm	Mid-IR 5 μm — 8 μm
CCD	Rad. hardness		
CMOS	🟨		
EMCCD	🟦 Rad. hardness		
p-channel CCD	🟨		
Si PIN Hybrid	🟨		
HgCdTe Hybrid	🟨	🟨	🟨
HgCdTe APD Hybrid	🟦 Reduce dark current	🟦 Reduce dark current	
░ MKID array	🟦 TRL < 5	🟦 TRL < 5	🟦 TRL < 5
░ TES array	🟦 TRL < 5	🟦 TRL < 5	🟦 TRL < 5
░ SNSPD	▧ Reduce dark current	▧ Reduce dark current	▧ Reduce dark current
░ Si:As Hybrid	░	░	░

🟩 TRL ≥ 6; Sufficiently mature for pre Phase-A
🟦 Promising technology, more work needed in specific areas
▧ Promising technology
░ Cryogenic cooling required
🟨 May be worth looking into with additional optimization

Rauscher et. al. 2015

Segment Phasing Sensing and Control
Telescope Vibration Control

Description	Current Capabilities	Desired Capabilities
Multi-segment large aperture mirrors require phasing and rigid-body sensing and control of the segments to achieve tight static and dynamic wavefront errors.	6 nm rms rigid body positioning error and 49 nm rms stability (JWST error budget) SIM and non-NASA: nm accuracy and stability using laser metrology	Systems-level considerations to be evaluated but expect will require less than 10 pm rms accuracy and about 1 pm rms stability.

Description	Current Capabilities	Desired Capabilities
Isolation and damping of spacecraft and payload vibrational disturbances	80 dB attenuation at frequencies > 40 Hz (JWST passive isolation) Disturbance Free Payload demonstrated at TRL 5 with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing.	Monolith: 120 dB attenuation at frequencies > 20 Hz. Segmented: 140 dB attenuation at frequencies > 40 Hz.

Next Steps to Closing Technology Gap

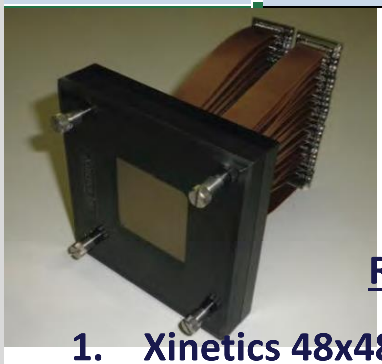
1. **These are systems-level challenges and will require specific point designs enabling specific trades. Both HabEx and LUVOIR will commence architecture studies in CY16.**
   - ❑ WFIRST coronagraph LOWFS/C results will be important
   - ❑ WFIRST telescope disturbance simulator will become available for future coronagraph testbed demonstrations at the HCIT; segmented mirror demonstrator expected in CY17 or CY18

Deformable Mirrors

Description	Current Capabilities	Desired Capabilities
Environment-tested, flight-qualified large format deformable mirrors	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10-9 contrasts in a vacuum environment and 10% bandwidth; 48x48 DM passed random vib testing.	4 m primary: ≥ 96x96 actuators 10 m primary: ≥ 128x128 actuators Enable raw contrasts of $\leq 10^{-9}$ at ~20% bandwidth and IWA ≤ 2.5 λ/D Flight-qualified device and drive electronics (radiation hardened,environmentally tested, life-cycled including connectors and cables) Large segment DM needs possible for segmented telescopes.

Possible Next Steps to Closing Technology Gap

- flight qualify the drive electronics (WFIRST; FY16-17)
  - ☐ re-designing the electronic inter-connectors to the actuators
  - ☐ miniaturizing the drive electronics
  - ☐ life test the DM actuators
  - ☐ complete environment testing
- MEMS DMS from BMC and Iris AO conducting dynamic testing (TDEMs; FY17)
- LUVOIR/HabEx studies to determine format size need (FY16-17)
  - ☐ still need large format development
  - ☐ large segmented DMs trade



Recent Activities

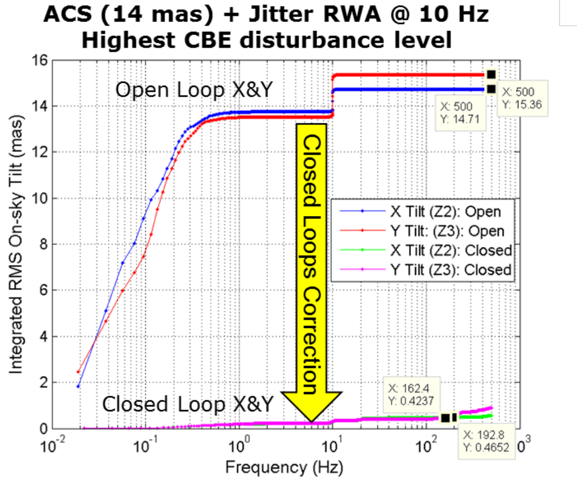
1. Xinetics 48x48 DMs connectorized and driver electronics built for HCIT (WFIRST)
2. Demonstrated as part of the coronagraph design serving as a wavefront apodizer (HLC for WFIRST)
3. Two DM configuration used to pass broadband coronagraph demo for WFIRST ($<10^{-8}$ contrast; 3 λ/D)

Low-Order Wavefront Sensing and Control

Description	Current Capabilities	Desired Capabilities
Sensing and control of line of sight jitter and low-order wavefront drift	≤ 0.5 mas rms LOS error residual in three axes from a 14 mas jitter input and fast-steering mirror control; ~ 100 pm rms sensitivity of focus (WFIRST). Higher low-order modes sensed to 10-100 nm WFE rms on ground-based telescopes.	Sufficient fast line of sight jitter (< 0.5 mas rms residual) and slow thermally-induced (≤ 10 pm rms sensitivity) WFE sensing and control to maintain closed-loop $< 10^{-9}$ raw contrast with an obscured/segmented pupil and simulated dynamic environment.

Next Steps to Closing Technology Gap

1. WFIRST LOWFS/C prototype integrated into coronagraph testbed in the JPL HCIT in summer 2016 where it will be tested to sense jitter and other thermally-induced low-order Zernike modes.
    - Testbed will include both a WFIRST telescope pupil and environment disturbances simulator.
2. Apply WFIRST LOWFS/C sensing and control technique to LUVOIR and HabEx concepts (FY17).
3. Design, build, and demonstrate performance on a segmented mirror testbed in the HCIT (FY17).



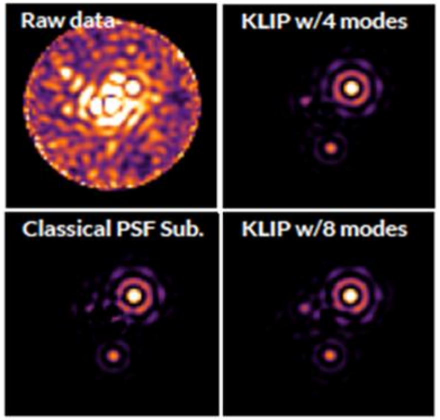
ACS (14 mas) + Jitter RWA @ 10 Hz
Highest CBE disturbance level

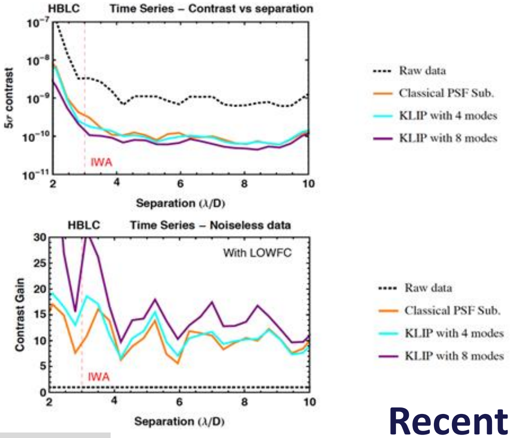
Recent Activities

1. WFIRST coronagraph baselined Zernike wavefront sensor.
2. A LOWFS/C testbed was designed and built in the HCIT
3. Testbed met WFIRST pointing requirements attenuating 14 mas jitter to ≤ 0.5 mas rms residual in vacuum

Post-Data Processing

Description	Current Capabilities	Desired Capabilities
Post-data processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-5}, dominated by phase errors.	A 10-fold contrast improvement in the visible from 10^{-9} raw contrast where amplitude errors are expected to be important (or a demonstration of the fundamental limits of post-processing)





Possible Path to Closing Technology Gap

1. **Develop simulated PSF library from the first set of 10% broadband HCIT data from WFIRST coronagraphs (CY16-18).**
    - Will include different types of simulations (e.g. telescope rolls) with full photon noise statistics and spurious detector and IFS effects
2. **Demonstrate algorithm by retrieving simulated planet through PSF subtraction. (CY16-18)**

Recent Activities

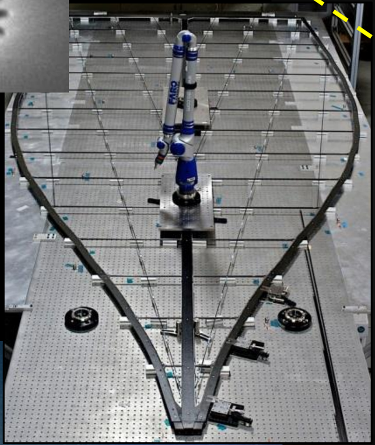
Working with STScI, the WFIRST team has simulated a full observing sequence (56h):

- consistently modeled the expected variations of residual speckles fields
- applied the KLIP post-processing algorithm to predict final contrast.
- ADI is very promising in its ability to reject background speckles.

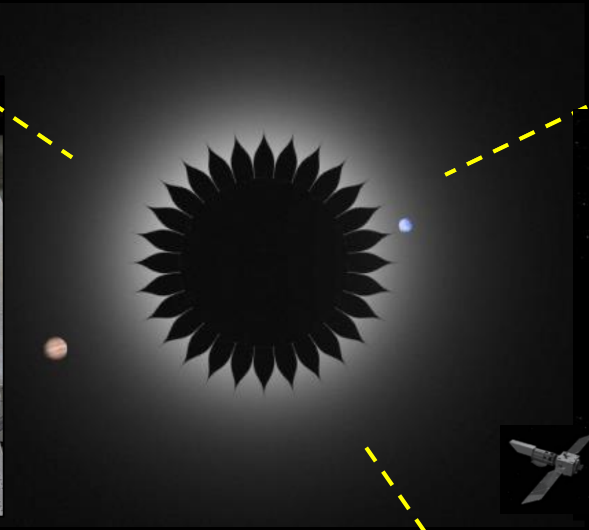
Starshade Technology Needs

Diffraction and Scattered Light Control

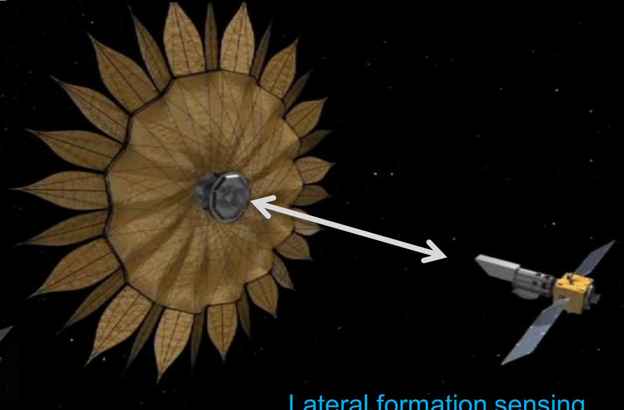
Solar glint



Petal shape



Lateral Formation Flying Sensing

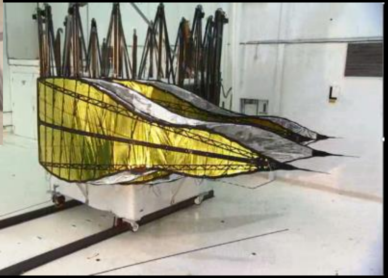


Lateral formation sensing

Optical demonstration and optical model validation

Precision Deployable Structures

Inner disk deployment



Petal unfurling

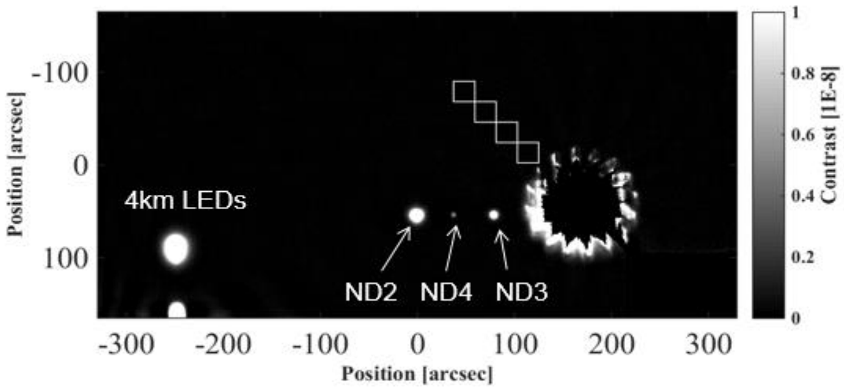
Recent Starshade Technology News

1. **NASA HQ has requested a Phase A review to consider projectizing the starshade technology development effort.**
    - Review set for Feb 19; ExEP will lead the review
    - Outcome of a favorable review would be a 3-4 yr technology project whose objective would be advancing the technology status of the starshade to TRL 5.
    - Multi-institutional participation

2. **Starshade Readiness Working Group (SRWG) commencing in January/February 2016.**
    - Objective is to identify the optimal path to flight for a starshade mission.
    - Multi-institutional working group and participation

Optical Performance and Model Validation

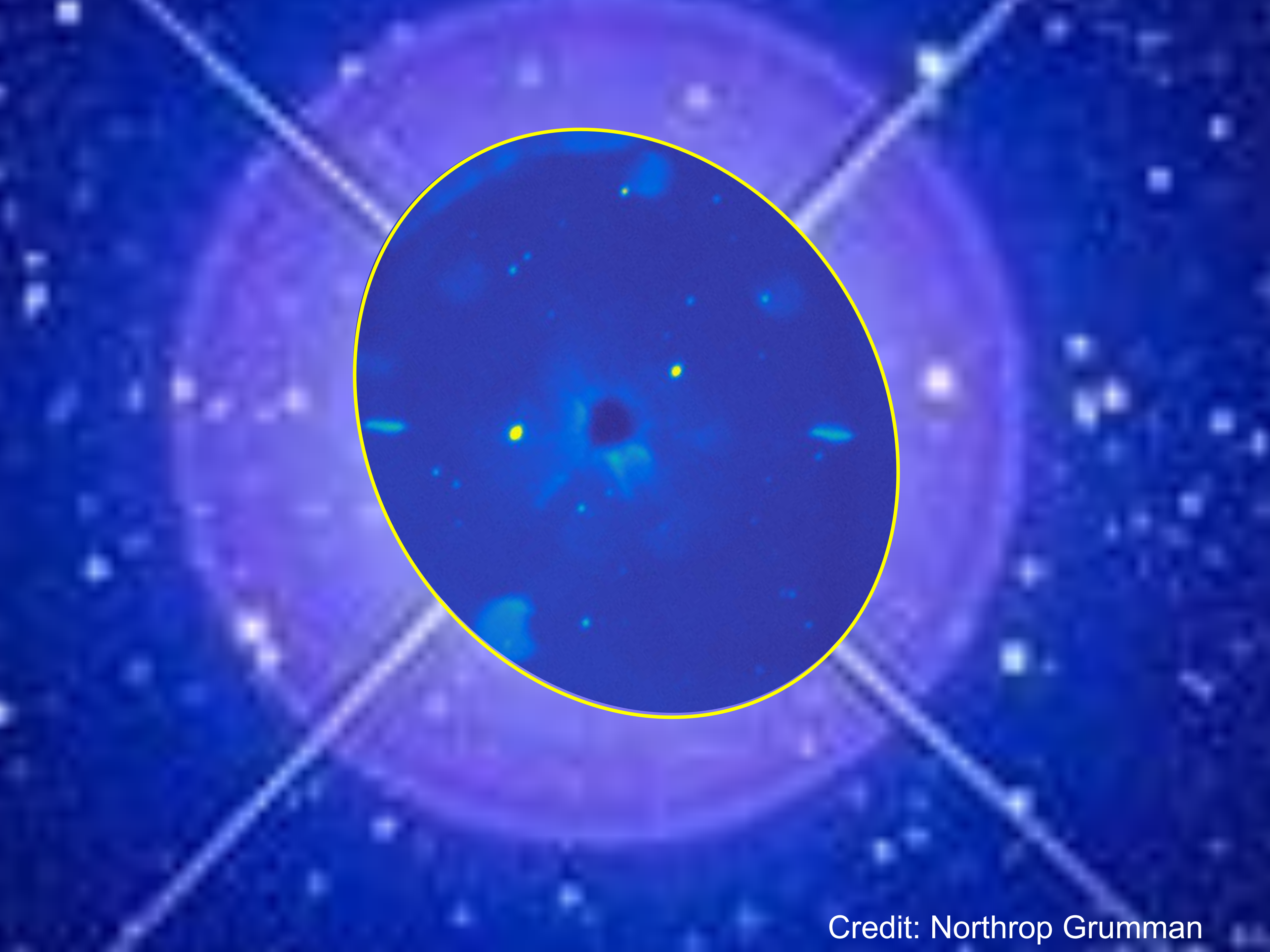
Description	Current Capabilities	Desired Capabilities
Experimentally validate the equations that predict the contrasts achievable with a starshade.	3×10^{-10} contrast at 632 nm, 5 cm mask, and ~500 Fresnel #; validated optical model 9×10^{-10} contrast at white light, 58 cm mask, and 210 Fresnel #	Experimentally validated models of contrast to $\leq 10^{-10}$ at Fresnel numbers < 30 across a broadband optical bandpass.



Recent Activities

- NGAS completed their TDEM-13 optical demonstration in a dried lake bed in NV
  - Reached 9×10^{-9} at a petal edge
  - Modelling results reasonably matched
- Proof of concept demonstrated using a heliostat at the McMath Solar Observatory

Credit: Northrop Grumman



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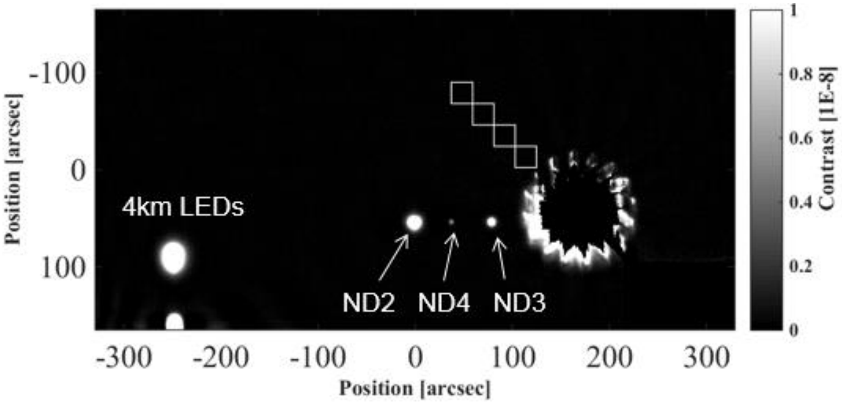
Possible Next Steps to Closing Technology Gap

- **Princeton demonstration and modeling validation at flight-like Fresnel**
  - ➢ first light and completion in CY16
- **NGAS and Colorado McMath Solar Observatory longer baseline demonstrations (CY16).**
  - ➢ Targeting Fomalhaut disk
- **Additional long baseline demonstrations?**



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  - ➢ Reached 9x10^{-9} at a petal edge
  - ➢ Modelling results reasonably matched
- **NGAS proof of concept using a heliostat at the McMath Solar Observatory**
- **Princeton TDEM 78m optical demonstration testbed near completion**

Solar Glint

Description	Current Capabilities	Desired Capabilities
Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (10 um); etched metal edges meet all specs but in-plane shape tolerance.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 µm, precise shape (≤ 20 µm rms), and reflectivity ≤ 12%.

Possible Next Steps to Closing Technology Gap

- **NG will identify edge materials that meet env't requirements and complete their scattered light demonstrations in CY16.**
- **JPL will attempt to modify the chemical etching process of amorphous metal to meet the stiffness requirement(CY16)**
    - will also revisit several candidate metals (including stainless steel)
- **Characterize the sensitivity of edge scatter performance to dust that can be attracted to statically charged optical edges (CY17)**
- **A TDEM-12 milestone led by Kasdin (Princeton) intends to verify solar glint performance fabricating a full-scale petal after testing to all relevant environments (CY17-18)**

Figure 1: Examples of Acktar coated samples. From left to right, Aluminum, Titanium, and BeCu substrates. The "back" side of all the samples is shown that would face away from the telescope. The sharp edge is the side to the right, with the bevel side shown.

Recent Activities

- **chemically etched thin strips of amorphous metal showed in-plane shape error exceeding the allocated tolerance**
    - due to the redistribution of internal stresses upon the removal of material
- **NG has identified three metal candidates in which it is advancing towards env't testing and scatter modeling.**

Petal Unfurling

Description	Current Capabilities	Desired Capabilities
Demonstrate petals unfurl in a controlled deployment without edge contact.	Model simulations predict uncontrolled petal unfurling produces edge contact.	Controlled petal unfurling mechanism demonstrated with no edge contact; includes integrated petal restraint mechanism. Modeling predicts petals are restrained during launch with margin.

Possible Next Steps to Closing Technology Gap

- Roccor to design and fabricate a Petal Unfurling Testbed to demonstrate latching and petal interface. (CY16)
  - Petal spines will be full-scale (7m)
- Roccor and JPL to upgrade the Petal Unfurling Testbed to demonstrate controlled unfurling of full-scale petals (CY17)

Recent Activities

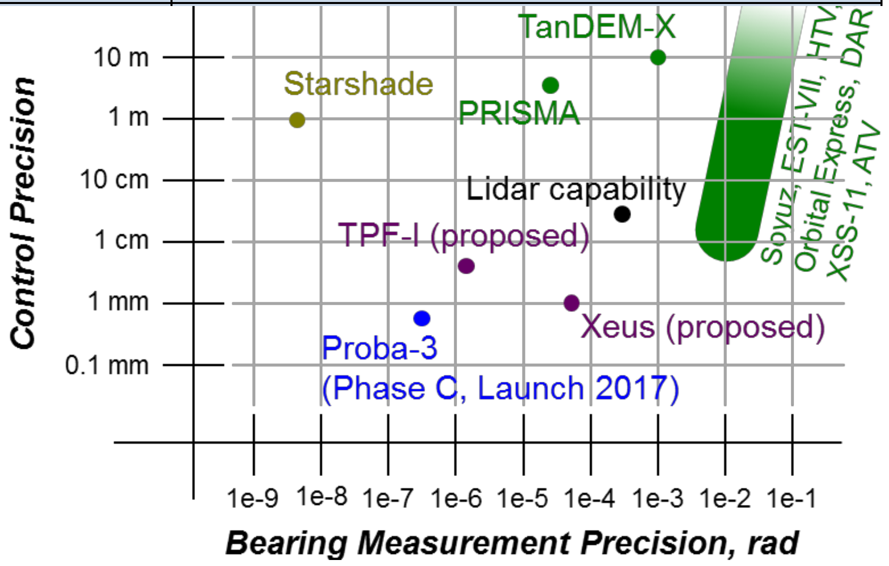
- SBIR partner Roccor and JPL produce preliminary design for unfurling and petal restraint mechanisms.

Lateral Formation Sensing

Description	Current Capabilities	Desired Capabilities
Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid star positions to ≤ 1/100th pixel with ample flux. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.30m accuracy at scaled flight separations (mas bearing angle). Estimated centroid positions to ≤ 1/40th pixel with limited flux from out of band starlight. Control algorithms demonstrated with scaled lateral control errors corresponding to ≤ 1m.

Possible Next Steps to Closing Technology Gap

- Kasdin TDEM to demonstrate a focal plane imaging sensor using same 78m testbed as with their optical performance demonstrations. (FY16-17)
- Cash TDEM to demonstrate a pupil plane imaging sensor in the same Nevada dry lake bed as Northrop Grumman used.



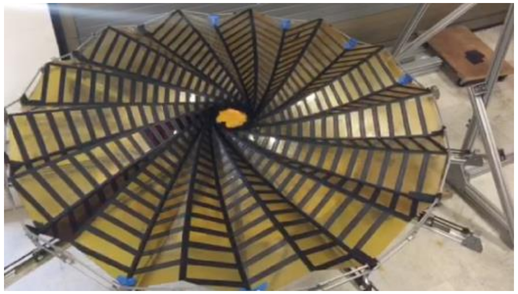
Recent Activities

Two TDEMs for conducting scaled test demonstrations for lateral sensoring were awarded to Web Cash and Jeremy Kasdin.

Inner Disk Deployment

Description	Current Capabilities	Desired Capabilities
Demonstrate that a starshade can be autonomously deployed to within its budgeted tolerances after exposure to relevant environments.	Petal deployment tolerance (≲ 1 mm) verified with low fidelity 12m prototype and no optical shield; no environmental testing.	Demonstrate ≲ 1 mm deployment tolerance with flight-like, minimum half-scale inner disk, with simulated petals, optical shield, and interfaces to launch restraint after exposure to relevant environments.

10m Inner Disk Testbed at JPL



2m Optical Shield Testbed at JPL

Next Steps to Closing Technology Gap

- 5m optical shield testbed will allow larger prototype development (FY16)
- Integrate optical shield into 10m inner disk testbed (FY16-17)
- Verify inner disk deployment tolerances (FY17)
- Conduct env't testing (FY18)

Recent Activities

- 10m inner disk testbed was completed in 2014.
- 2m testbed completed for demonstrating origami shield designs.
- TDEM-13 awarded for optical shield design and integration into 10m inner disk testbed (Mark Thomson/JPL).

Inner Disk Prototype Deployment Trial at JPL

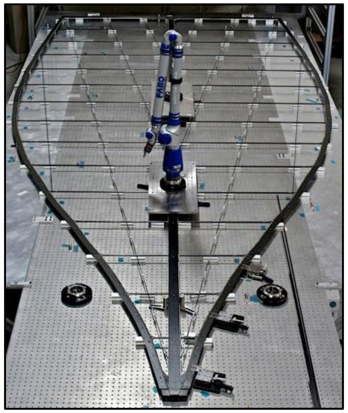
Optical Shield Prototype Deployment Trial at JPL

Petal Shape

Description	Current Capabilities	Desired Capabilities
Demonstrate a high-fidelity, flight-like starshade petal meets petal shape tolerances after exposure to relevant environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6m prototype and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements.	Demonstrate a flight-like, full-scale petal (~ 7m) fabricated to within 200 μm of shape tolerances and maintains shape after multiple deployments from stowed configuration.

Next Steps to Closing Technology Gap

- **Kasdin TDEM will complete the detailed petal design, produce a flight-like, full-scale prototype with optical edges and optical shield, and test it to relevant environments. (CY17-18)**
  - ☐ The petal shape will be verified multiple times with deployment testing from a stowed configuration in between.



Recent Activities

In 2015, a TDEM-12 activity led by PI Kasdin and JPL co-I's developed a new preliminary petal design that incorporates flight-like :

- **optical edges**
- **optical shield**
- **interfaces to launch restraint and deployment control mechanisms.**

Backup Slides

Coronagraph Technology Gap Prioritization

Gap ID	**Gap Title**	**Impact**	**Urgency**	**Trend**	**Total**
CG-2	Coronagraph Architecture	4	4	3	11
CG-1	Large Aperture Mirrors	4	2	4	10
CG-8	Visible Ultra-Low Noise Detector	4	3	2	9
CG-9	NIR Ultra-Low Noise Detector	4	2	3	9
CG-6	Segment Phasing Sensing & Control	4	2	3	9
CG-7	Telescope Vibration Control	4	2	3	9
CG-5	Deformable Mirrors	4	2	2	8
CG-3	Low-Order Wavefront Sensing and Control	4	2	2	8
CG-4	Post-Data Processing	4	2	2	8

Starshade Technology Gap Prioritization

Gap ID	Gap Title	Impact	Urgency	Trend	Total
S-2	Optical Performance Demonstration and Optical Modeling	4	4	3	11
S-1	Control Edge-Scattered Sunlight	4	4	3	11
S-6	Petal Unfurling	4	3	3	10
S-3	Lateral Formation Flying Sensing	4	3	2	9
S-5	Inner Disk Deployment	4	3	2	9
S-4	Petal Shape	4	3	1	8

Prioritization Criteria Definition

Impact:	4: Critical and key enabling technology - required to meet mission concept objectives; without this technology, applicable missions would not launch
	3: Highly desirable - not mission-critical, but provides major benefits in enhanced science capability, reduced critical resources need, and/or reduced mission risks; without it, missions may launch, but science or implementation would be compromised
	2: Desirable - not required for mission success, but offers significant science or implementation benefits; if technology is available, would almost certainly be implemented in missions
	1: Minor science impact or implementation improvements; if technology is available would be considered for implementation in missions
Urgency:	4: In time for the Decadal Survey (2019)
	3: LD < 10 yr (< 2025)
	2: LD < 15 yr (< 2030)
	1: LD > 15 yr (> 2030)
Trend:	4: Very large perceived risk of not being ready in time: (a) no ongoing current efforts (b) little or no funding allocated
	3: Large perceived risk of not being ready in time: (a) others are working towards it but little results or their performance goals are very far from the need, (b) funding unclear, or (c) time frame not clear
	2: Medium perceived risk of not being ready in time: (a) others are working towards it with encouraging results or their performance goals will fall short from the need, (b) funding may be unclear, or (c) time frame not clear
	1: Small perceived risk of not being ready in time: (a) others are actively working towards it with encouraging results or their performance goals are close to need, (b) it's sufficiently funded, and (c) time frame clear and on time

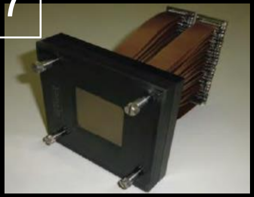
Coronagraph Technology Needs

Contrast

1

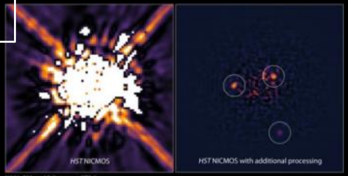
Coronagraph architectures

7



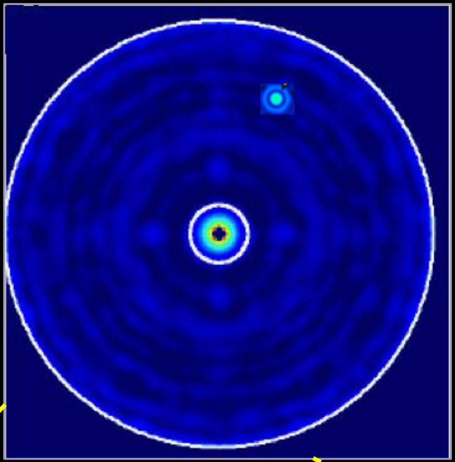
Deformable mirrors

9



NASA, ESA, and R. Soummer (STScI)

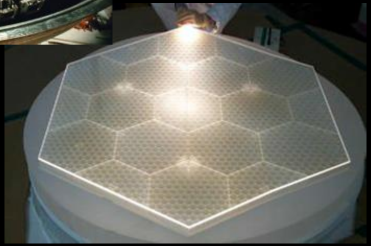
Image post-processing



2

Angular Resolution

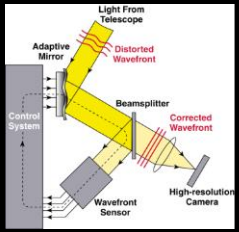
Large monolith



Segmented

Contrast Stability

8



Low-order wavefront control

5

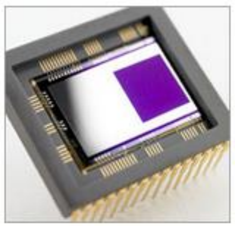
Segment phasing and rigid body control

6

Telescope vibration control

Detection Sensitivity

3



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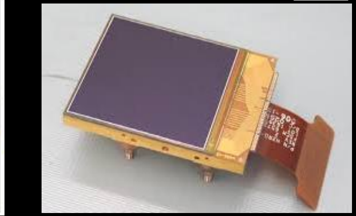
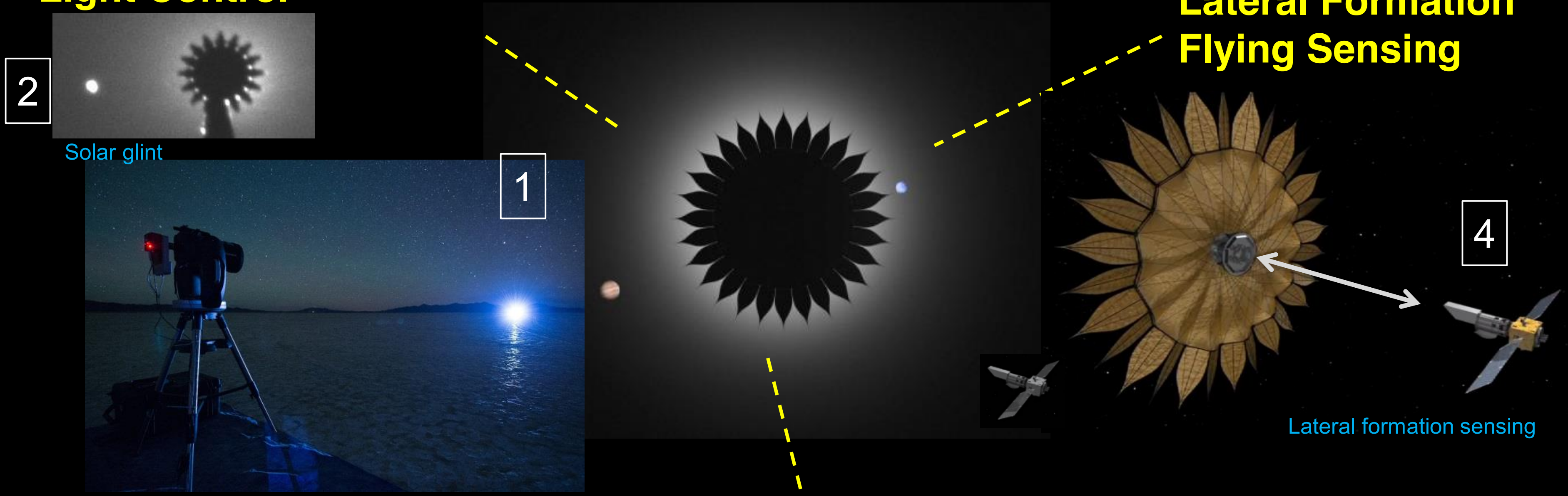


Ultra-low noise detectors
(visible and infrared wavelengths)

Starshade Technology Needs

Diffraction and Scattered Light Control

Lateral Formation Flying Sensing

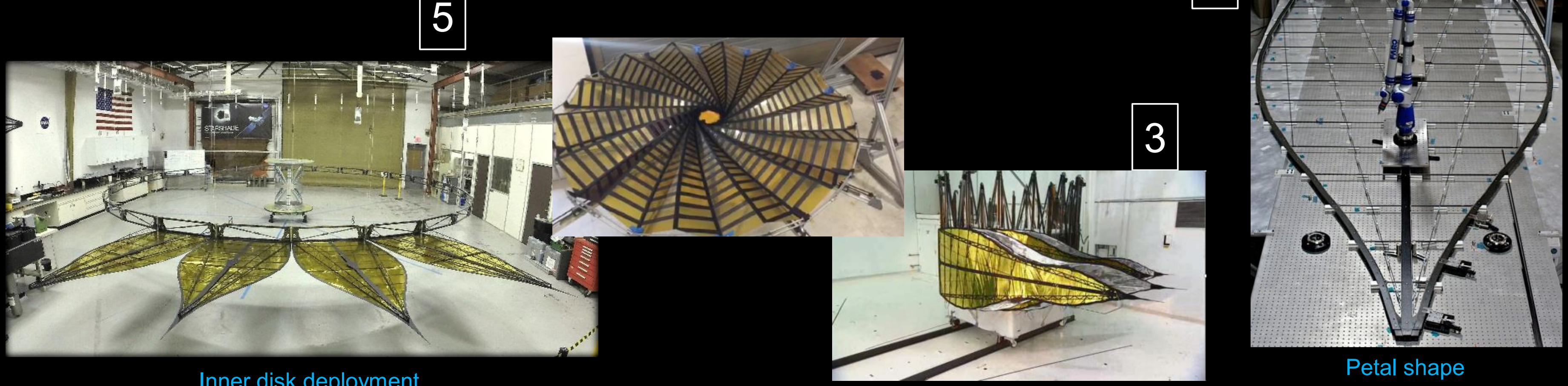


Solar glint

Optical demonstration and optical model validation

Lateral formation sensing

Precision Deployable Structures



Inner disk deployment

Petal lunfurling

Petal shape