ExEP Technology Needs and Status

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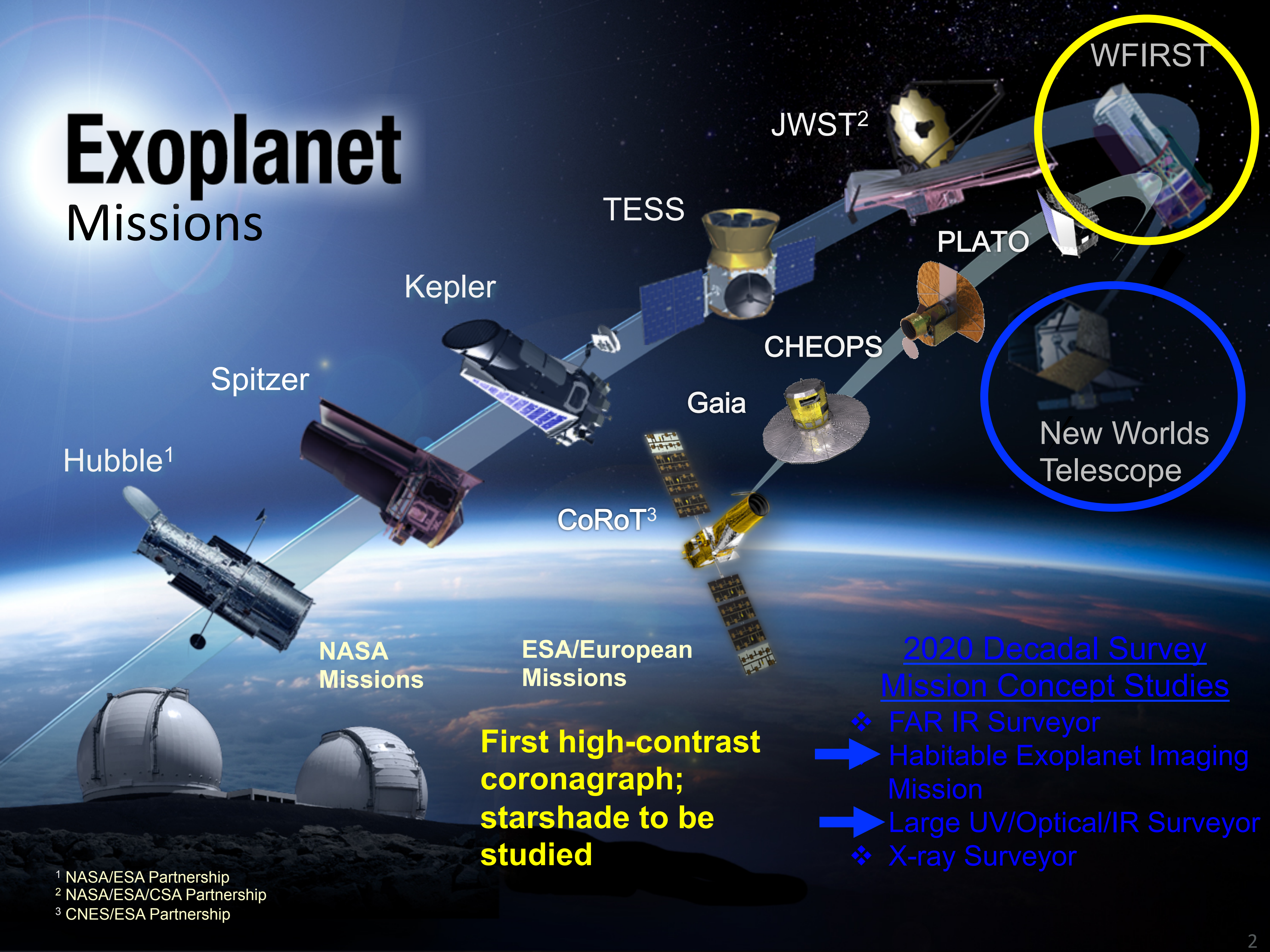
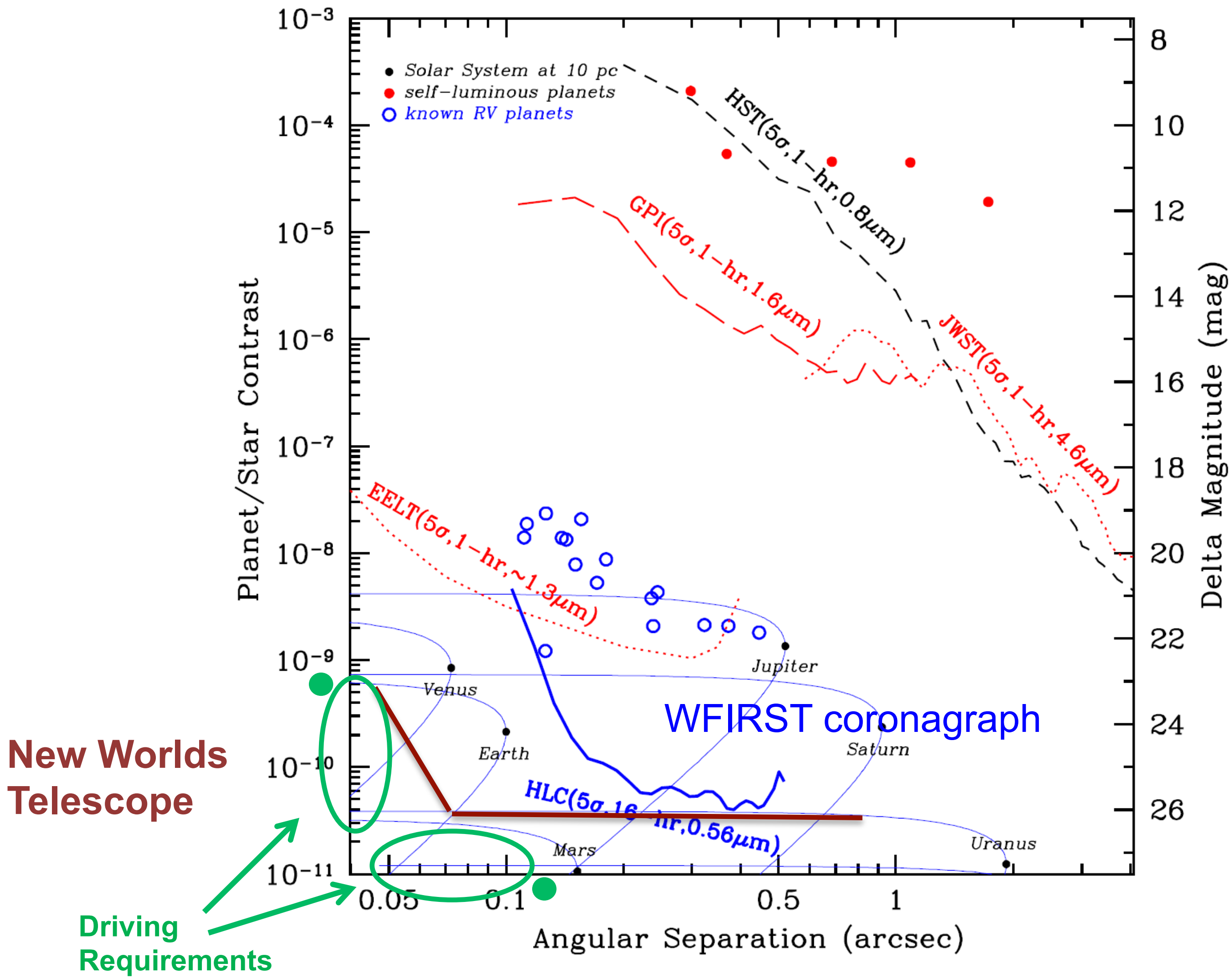
Program Chief Technologist

01/04/16
ExoPAG Meeting
2016 Kissimmee, FL

CL#15-5804

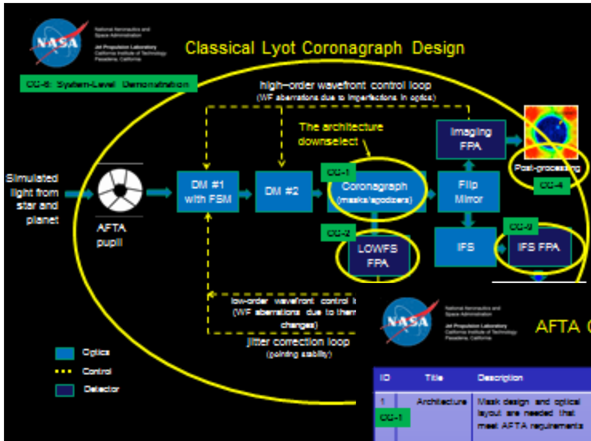

Exoplanet
Missions
Hubble[1]
Spitzer
Kepler
TESS
JWST[2]
WFIRST
PLATO
CHEOPS
Gaia
CoRoT[3]
New Worlds Telescope
NASA Missions
ESA/European Missions
First high-contrast coronagraph; starshade to be studied
2020 Decadal Survey Mission Concept Studies
❖ FAR IR Surveyor
Habitable Exoplanet Imaging Mission
Large UV/Optical/IR Surveyor
❖ X-ray Surveyor
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA Partnership

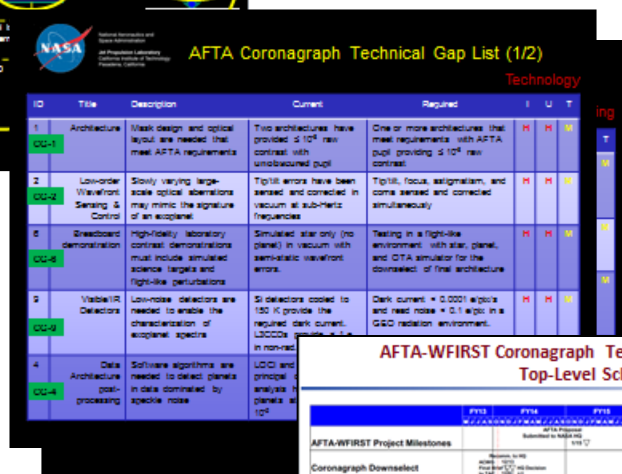
Driving Requirements for Imaging Exo-Earths

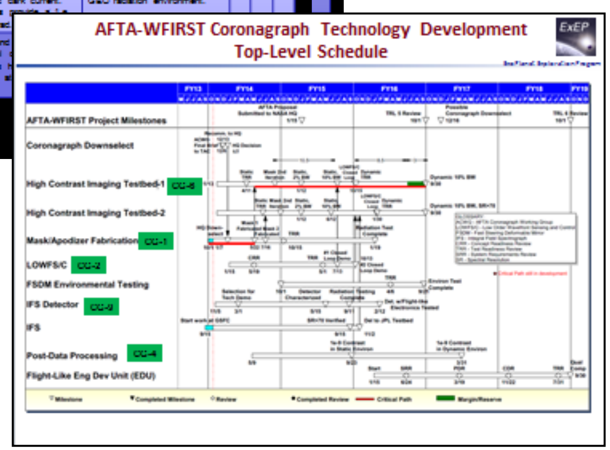


Credit: Wes Traub

ExEP Technology Development Process







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

ExEP Technology Gap Lists

JPL Document D-94249

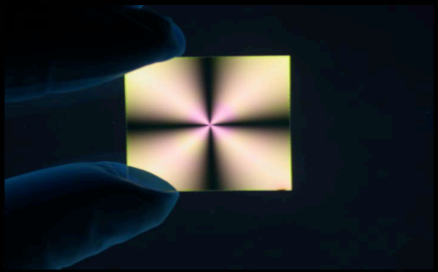
Exoplanet Exploration Program Technology Plan

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.

Next update by Jan 19, 2016

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 ar 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.

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

Today

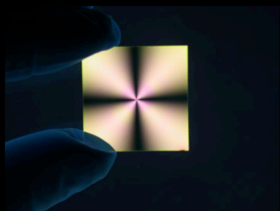
A. **Please listen for:**
   1. Completeness – Are there any gaps missing?
   2. Correctness – Are the "Needed Capabilities" the right ones?

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

C. **Please contact me anytime during the week or via email to discuss/edit anything you hear today.**

Coronagraph Technology Needs

Contrast



Coronagraph architectures

Deformable mirrors

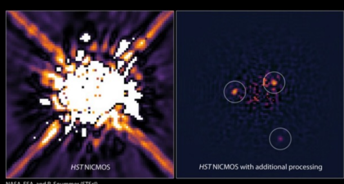
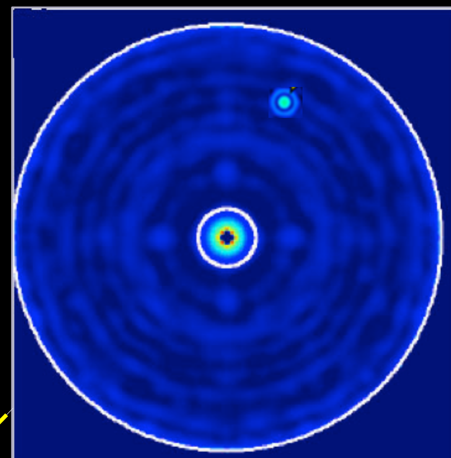
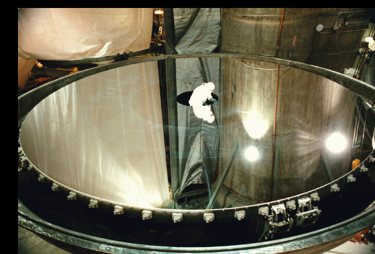


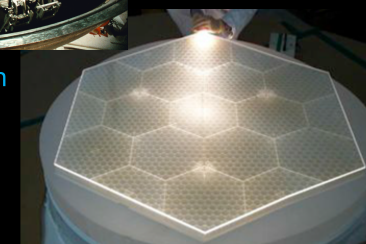
Image post-processing



Angular Resolution

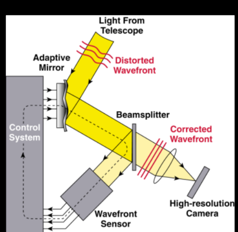


Large monolith



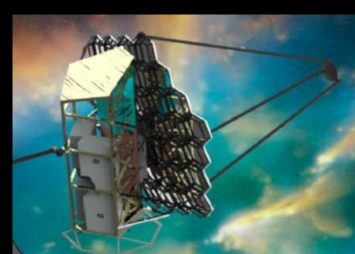
Segmented

Contrast Stability



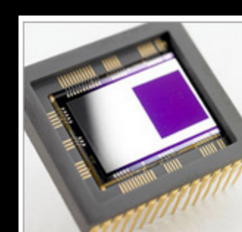
Low-order wavefront sensing and control

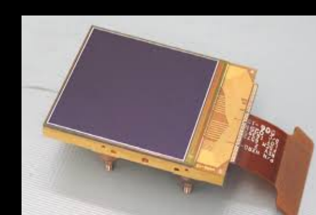
Segment phasing and rigid body sensing and control



Telescope vibration sensing and control

Detection Sensitivity

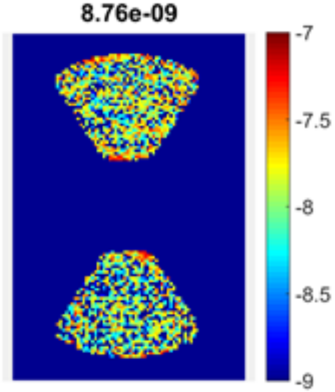


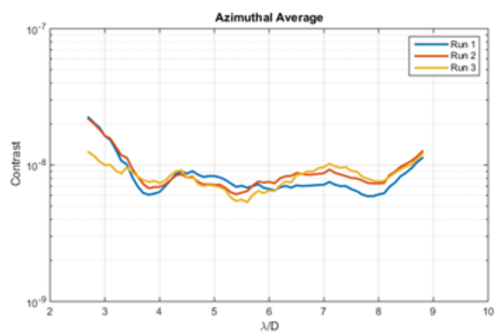


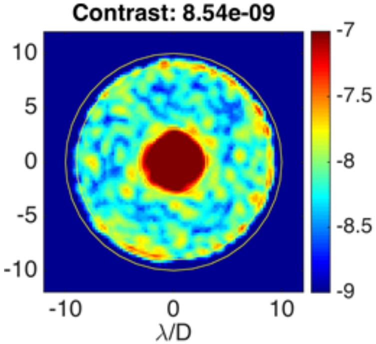
Ultra-low noise visible and infrared detectors

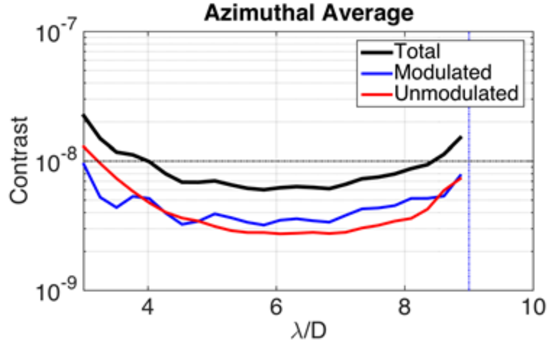
Coronagraph Architecture

Description	Current Capabilities	Needed 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) < 8.8×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab env't (WFIRST)	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts ≤ 10^{-9}, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured/segmented pupils in a simulated dynamic vacuum lab environment.









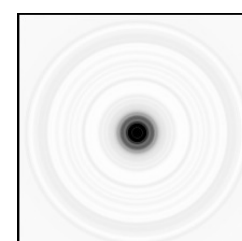
Recent Activities

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

Description	Current Capabilities	Needed 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) < 8.8×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab env't (WFIRST)	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts ≤ 10^{-9}, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured/segmented pupils in a simulated dynamic vacuum lab environment.

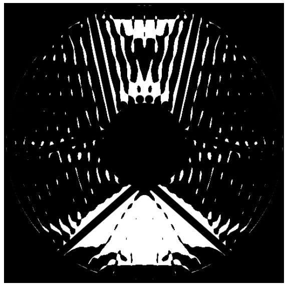
Possible Steps to Closing Technology Gap

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 in the HCIT (WFIRST; CY16)
3. Demonstrations of next generation coronagraphs at STScI, NASA-GSFC, and the ExEP HCIT (FY16-FY19)
4. ExEP Segment Coronagraph Design and Analysis (SCDA) effort (FY16)

Recent Activities

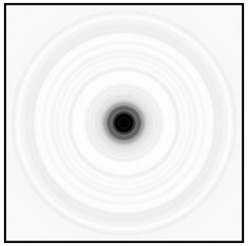
Both WFIRST coronagraph masks have achieved < 10^{-8} raw contrast at across a 3-9 λ/D symmetric dark hole with obscured pupil.

Shaped Pupil Mask



Black Si substrate with reflective patterned Al coating

Hybrid Lyot Mask

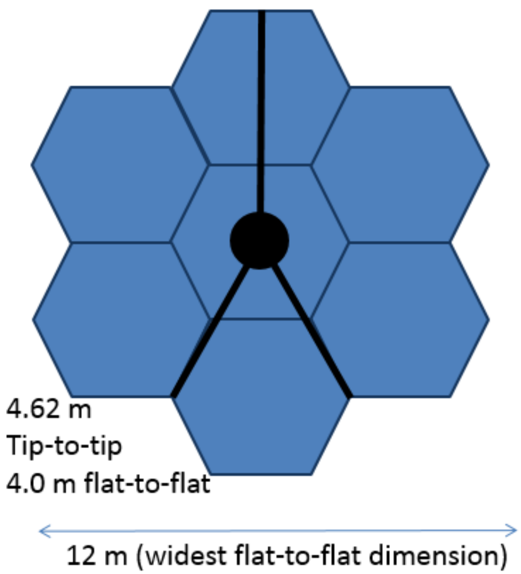


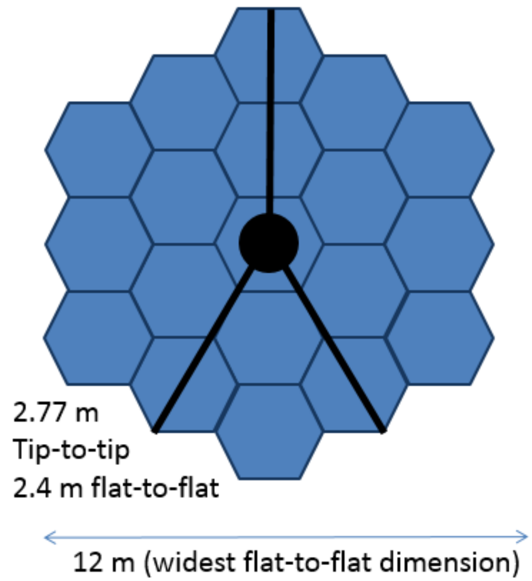
Circular mask with profiled Ni layer coated with patterned PMGI dielectric

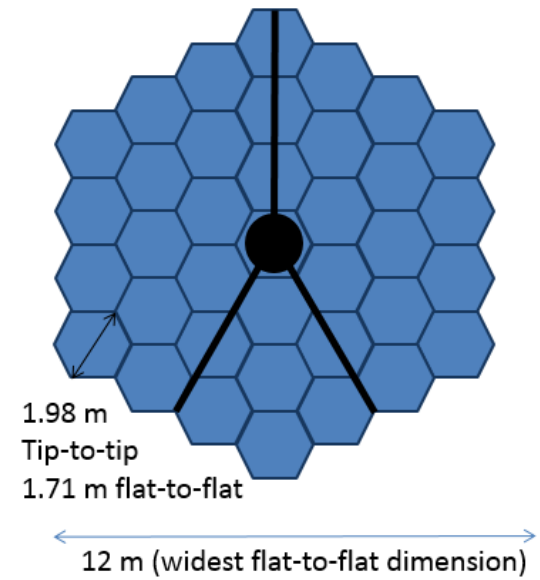
Coronagraph Architectures in the SCDA Study

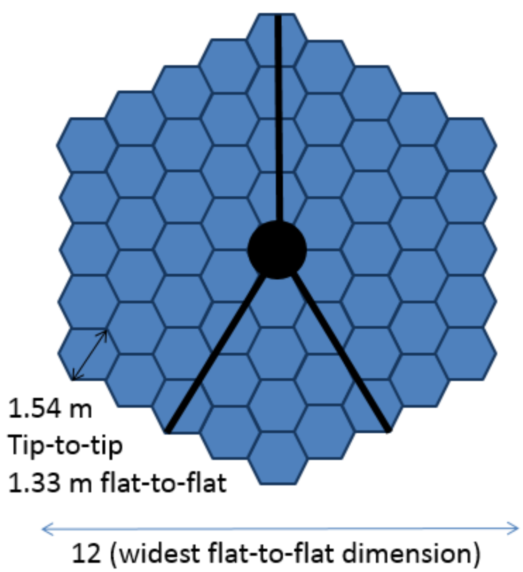
1. PIAA CMC (University of Arizona/NASA-Ames/JPL)
2. APLC/SPC (Space Telescope Science Institute/Princeton)
3. Vortex (Caltech/JPL)
4. Hybrid Lyot (Caltech/JPL)
5. Visible Nulling Coronagraph (NASA–GSFC)

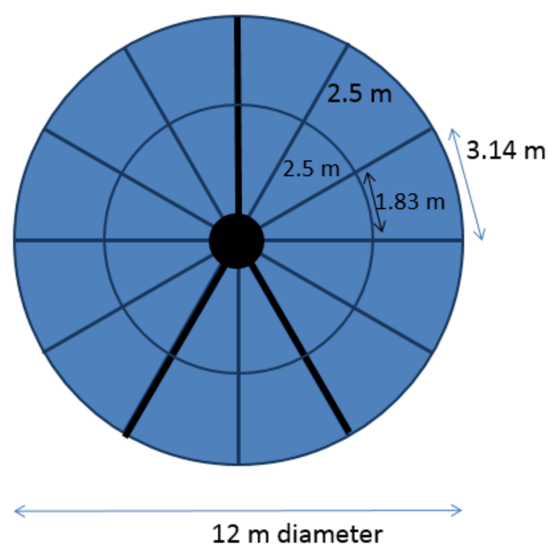
Reference Apertures Under Consideration in the SCDA Effort

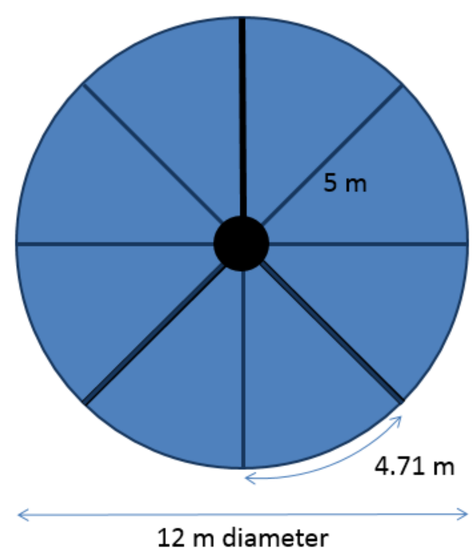










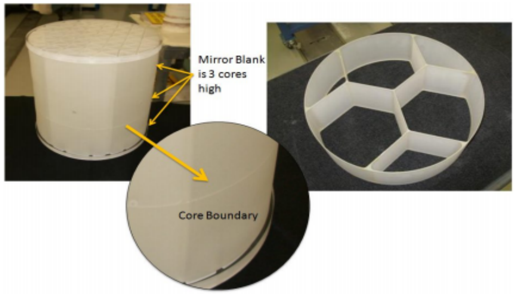


Large Aperture Primary Mirrors - Monoliths

Current Capabilities	Needed 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, 20 cm thick sub-scale model of a 4m ULE mirror to demonstrate lateral scalability of the stacked core process. (FY16-FY17)**
  - ❑ Will characterize 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/LUVOIR will study range of monolith architectures, conduct trades and modeling. (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 design study conducted by MSFC of 4m monolith on SLS (Block 1)**

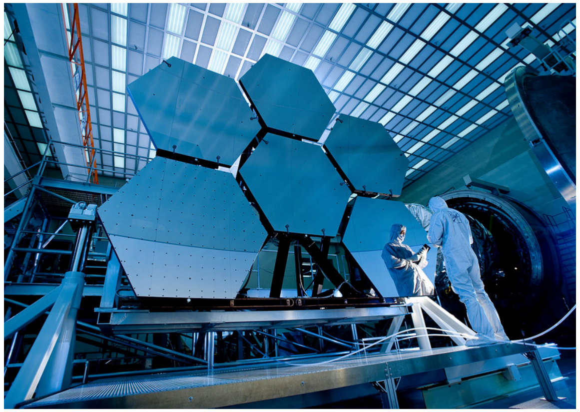
Large Aperture Primary Mirrors - Segmented

Exoplanet Exploration Program

Current Capabilities	Needed 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

- **HabEx/LUVOIR concept studies will define the architecture, materials, and operating wavelength range for a segmented telescope; modeling. (CY16-18)**
- **SCDA effort will identify which coronagraph architectures meet exo-earth imaging requirements on a segmented telescope. (CY16)**
  - Possible 2nd year added for SCDA adding dynamic disturbances and rigid-body segment errors (FY17)



JWST at MSFC's XRCF

Recent Activities

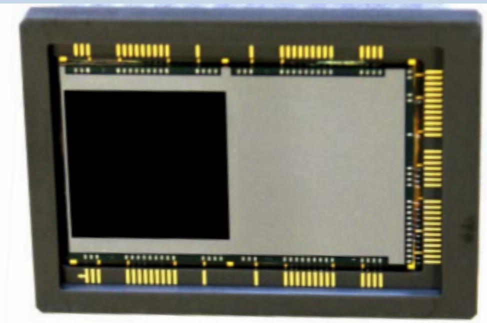
- **ATLAST wraps up after several years of design work; HDST report.**
- **ExEP SCDA effort begun**
  - creation of a reference aperture team

Ultra-Low Noise Visible Detector

Description	Current Capabilities	Needed 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 (WFIRST). 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. (CY16)
   - ❑ EMCCD 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
- Radiation testing completed
  - ❖ RN, dark current, CIC results all appear favorable

Ultra-Low Noise Infrared Detector

Exoplanet Exploration Program

Description	Current Capabilities	Needed 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 <u>space radiation environment</u> over mission lifetime. ≥ 2kx2k format

<u>Possible Next Steps to Closing Technology Gap</u>

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

Baselined by WFIRST → EMCCD

Being evaluated now → HgCdTe APD Hybrid

Cryogenic detectors: MKID array, TES array, SNSPD, Si:As Hybrid

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			

- (green) TRL ≥ 6; Sufficiently mature for pre Phase-A
- (blue) Promising technology, more work needed in specific areas
- (light blue) Promising technology
- (grey) Cryogenic cooling required
- (yellow) May be worth looking into with additional optimization

Rauscher et. al. (2015); SPIE

Segment Phasing Sensing and Control
Telescope Vibration Sensing and Control

Description	Current Capabilities	Needed 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 stability.

Description	Current Capabilities	Needed 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 end-to-end attenuation at frequencies > 20 Hz. Segmented: 140 dB end-to-end attenuation at frequencies > 40 Hz. End-to-end implies isolation between disturbance source and the telescope.

Next Steps to Closing Technology Gap

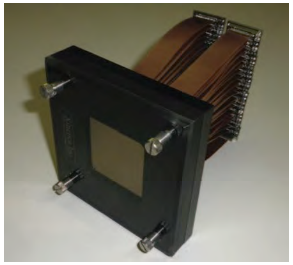
1. **These are systems-level challenges and will require specific point designs enabling specific trades. Both HabEx and LUVOIR will commence architecture studies in CY16.**
   - ❑ WFIRST coronagraph LOWFS/C results will be important
   - ❑ WFIRST telescope disturbance simulator will become available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

Deformable Mirrors

Description	Current Capabilities	Needed 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 ≤ 10^{-9} at ~20% bandwidth and IWA ≤ 3 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

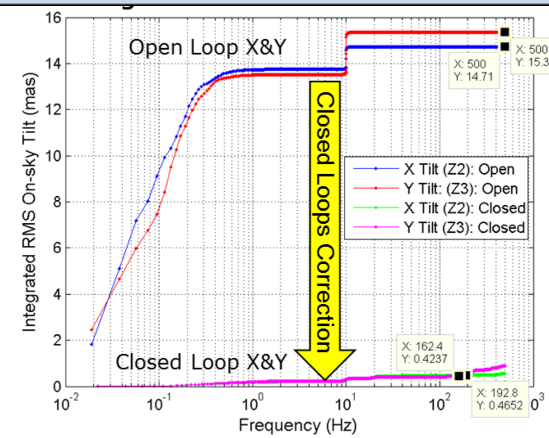
1. Xinetics 48x48 DMs connectorized and driver electronics built for HCIT (WFIRST)
2. Two DM configuration used to pass broadband coronagraph demo for WFIRST (< 10^{-8} contrast; 3-9 λ/D)
3. Demonstrated as part of the coronagraph design serving as a wavefront apodizer (HLC for WFIRST)

Low-Order Wavefront Sensing and Control

Description	Current Capabilities	Needed Capabilities
Sensing and control of line of sight jitter and low-order wavefront drift	< 0.5 mas rms per axis LOS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs; ~ 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. **Integrate LOWFS/C into a segmented mirror testbed in the HCIT (FY18-19).**

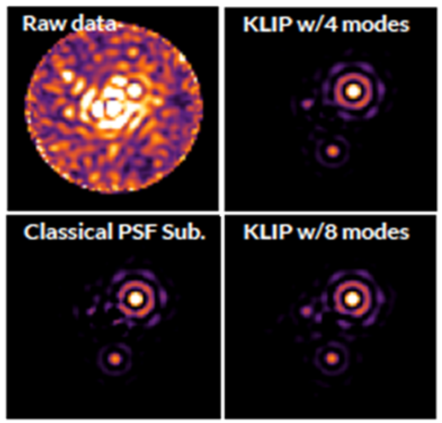


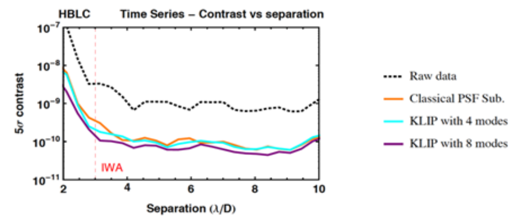
Recent Activities

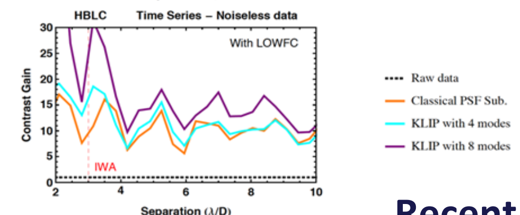
1. **WFIRST coronagraph baselined Zernike wavefront sensor.**
2. **A LOWFS/C testbed was designed and built in the HCIT**
3. **Testbed met WFIRST pointing requirements attenuating 14 mas jitter to < 0.5 mas rms residual in vacuum**

Post-Data Processing

Description	Current Capabilities	Needed 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

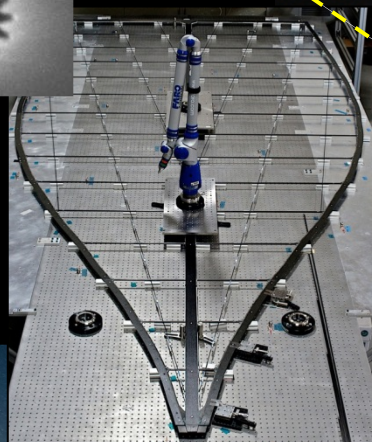
Working with STScI, the WFIRST team has simulated a full observing sequence (56h):

- 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.

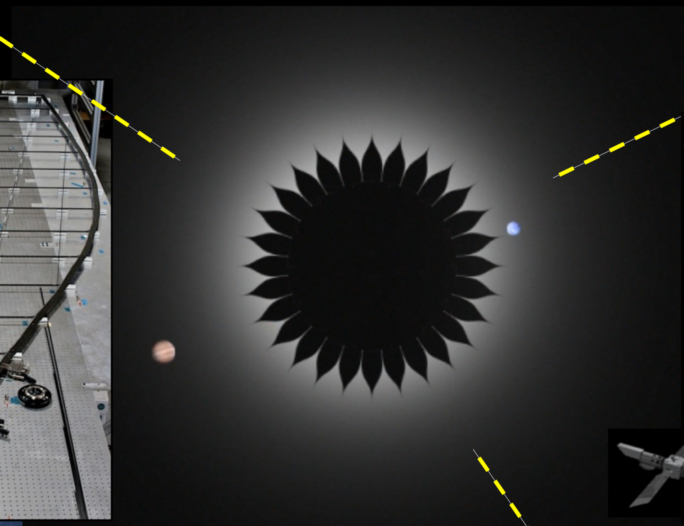
Starshade Technology Needs

Diffraction and Scattered Light Control

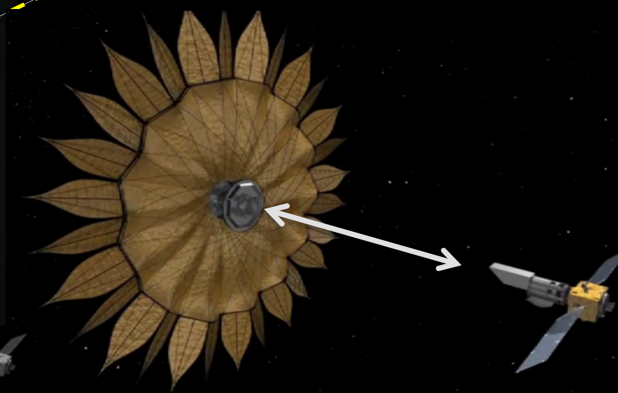
Solar glint



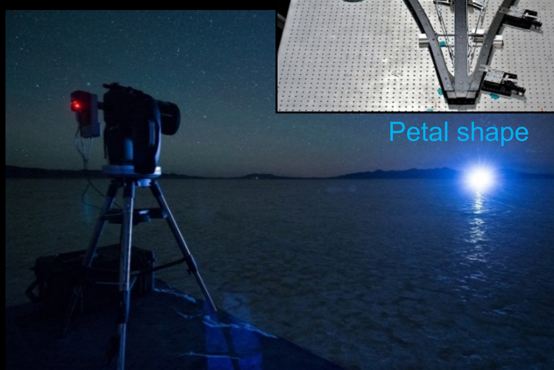
Petal shape



Lateral Formation Flying Sensing



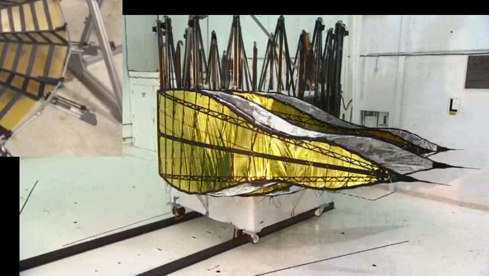
Lateral formation sensing



Optical demonstration and model validation

Precision Deployable Structures

Inner disk deployment



Petal deployment

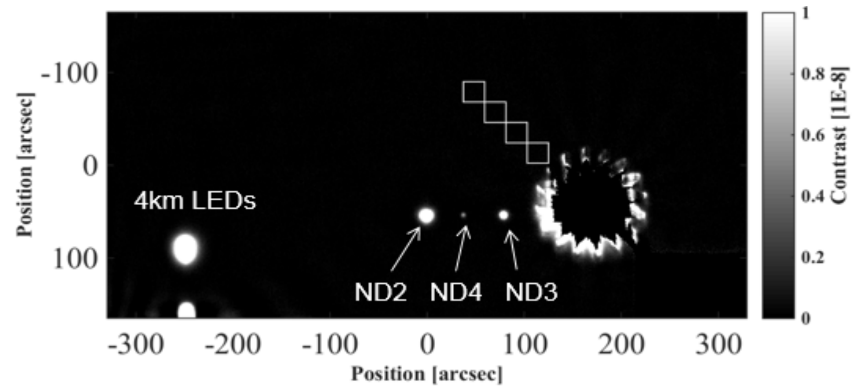
Recent Starshade Technology News

1. **NASA APD has scheduled a gate review (KDP-A) for a Starshade Technology Project to enter formulation phase.**
   – Review set for Feb 19
   – 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 during formulation phase
   – Will work with Blackwood and Seager to develop a “science team”

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

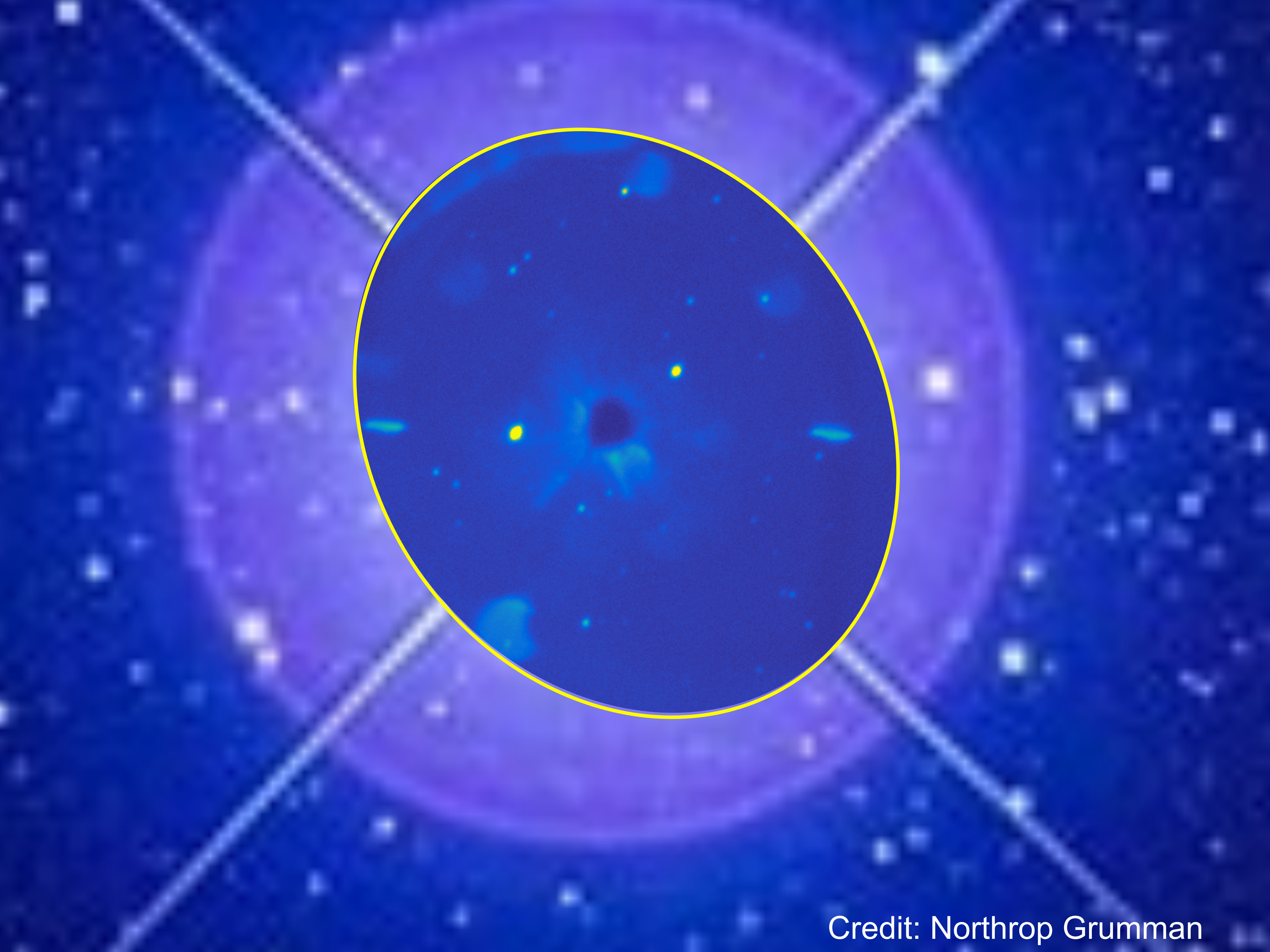
Optical Demonstration and Model Validation

Description	Current Capabilities	Needed 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 $\leq 10^{-10}$ in scaled flight-like geometry with Fresnel numbers ≤ 20 across a broadband optical bandpass.



Recent Activities

- NGAS completed their TDEM-12 (Glassman PI) optical demonstration in a dried lake bed in NV
  - Reached 9×10^{-10} at a petal edge
  - Modelling results to purposefully-flawed shades need work.
  - Additional tests completed in Nov
- Proof of concept demonstrated using a heliostat at the McMath Solar Observatory

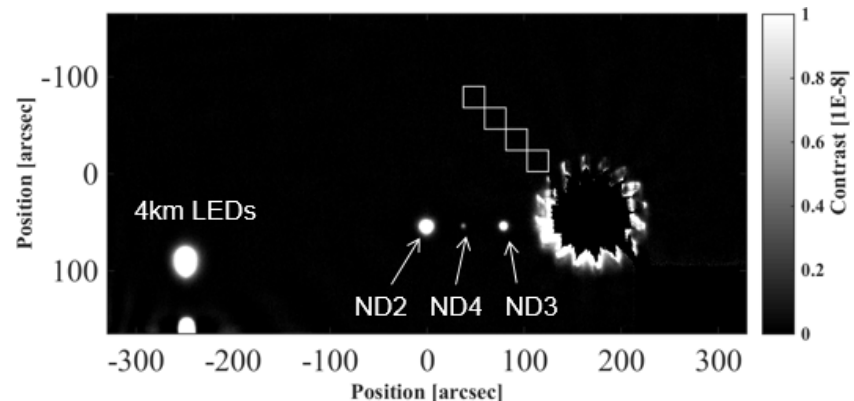

Credit: Northrop Grumman

Optical Performance and Model Validation

Description	Current Capabilities	Needed 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 $\le 10^{-10}$ in scaled flight-like geometry with Fresnel numbers $\le$ 20 across a broadband optical bandpass.

Possible Next Steps to Closing Technology Gap

- **Princeton TDEM demonstration (78m testbed) 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 welcomed; key, however, is model validation.**



Recent Activities

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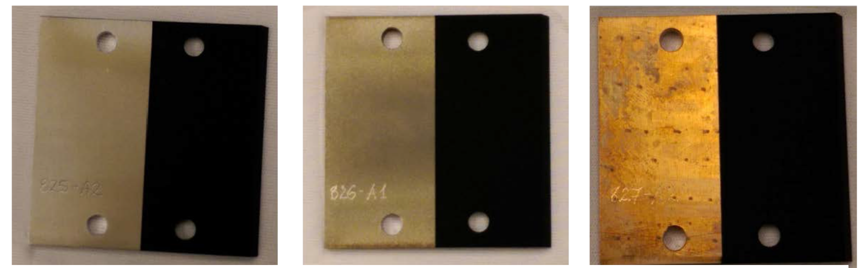
  - ➢ **Modelling results to purposefully-flawed shades need work.**
  - ➢ **Additional tests completed in Nov**
- **Proof of concept demonstrated using a heliostat at the McMath Solar Observatory**

Solar Glint

Description	Current Capabilities	Needed 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 (Exo-S design).	Integrated petal optical edges (1) meet and maintain precision in-plane shape requirements after deployment trials and (2) limit solar glint enabling 10^{-10} contrast at petal edges.

Possible Next Steps to Closing Technology Gap

- **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)
  - intend on characterizing the sensitivity of edge scatter performance to dust (CY17)
- **NG will identify edge materials that meet env't requirements and complete their scattered light demonstrations in CY16.**
- **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)**



In-process metal substrates under investigation by Casement TDEM-12.

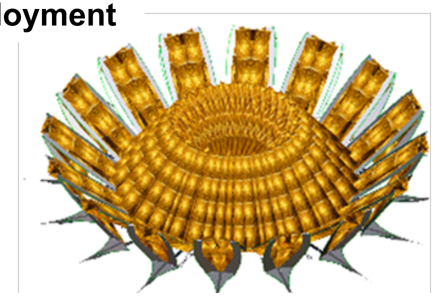
Recent Activities

- **NG TDEM-12 (PI Casement) has identified three metal candidates in which it is advancing towards env't testing and scatter modeling.**
- **Chemically etched thin strips of amorphous metal showed in-plane shape error exceeding the allocated tolerance (JPL)**
  - due to the redistribution of internal stresses upon the removal of material

Petal Deployment

Description	Current Capabilities	Needed Capabilities
Demonstrate petals deploy without edge contact.	Model simulations predict uncontrolled petal unfurling produces edge contact (Exo-S design).	Full-scale controlled petal deployment mechanism demonstrated to secure petals throughout launch and deploy with no edge contact.

Exo-S unfurling deployment



NG radial boom deployment

Possible Next Steps to Closing Technology Gap

- **Roccor to design and fabricate a full-scale petal unfurling testbed to demonstrate latching and petal interface. (CY16)**
  - Petal spines will be full-scale (7m)
  - NGAS to review designs; possible architecture trade

- **Roccor funded to upgrade the petal unfurling testbed to demonstrate controlled unfurling of full-scale petals (CY17)**

Recent Activities

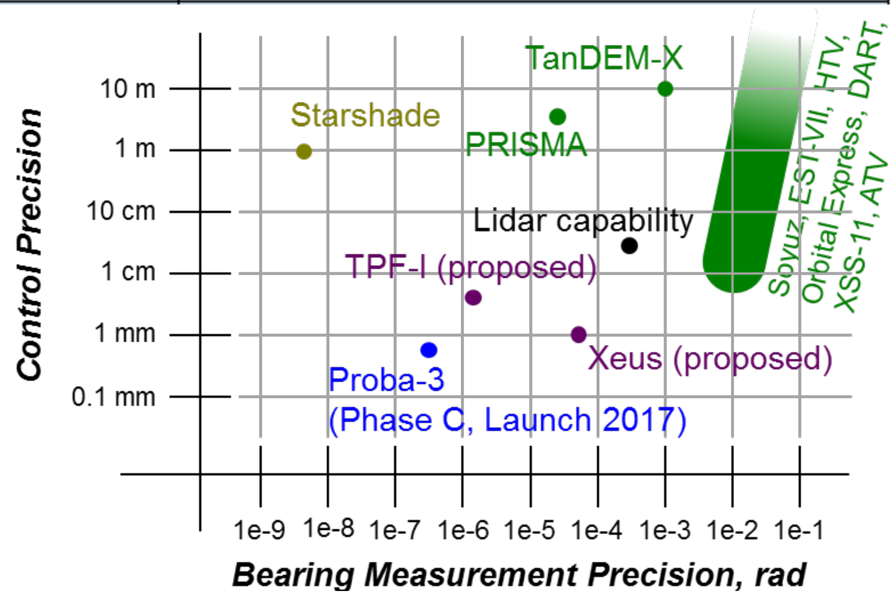
SBIR partner Roccor and JPL produce preliminary design for unfurling and petal restraint mechanisms.

Lateral Formation Sensing

Description	Current Capabilities	Needed 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

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

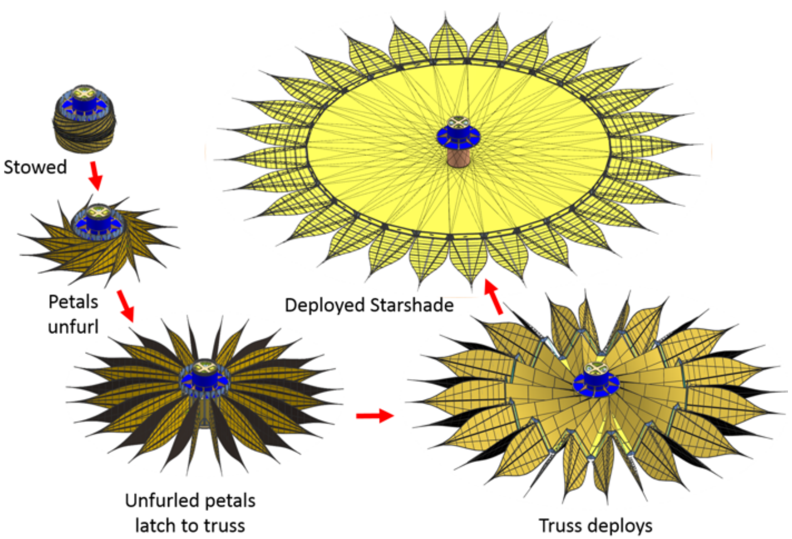


Recent Activities

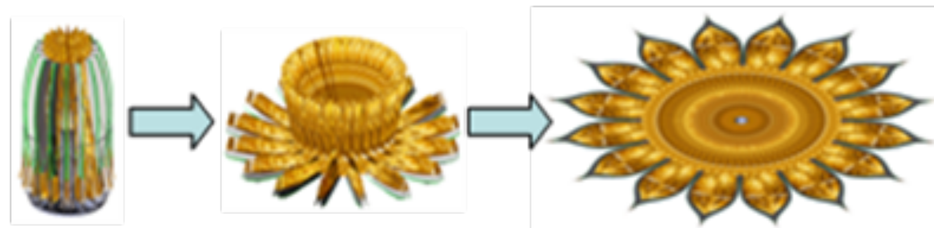
Two TDEMs for conducting scaled test demonstrations for lateral sensoring were awarded to Web Cash and Jeremy Kasdin.

Inner Disk Deployment

Description	Current Capabilities	Needed 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 (Exo-S design).	Demonstrate deployment tolerances are met with flight-like, minimum half-scale inner disk, with simulated petals, optical shield, and interfaces to launch restraint after exposure to relevant environments.



Exo-S starshade deployment concept



NGAS starshade deployment concept

Recent Activities

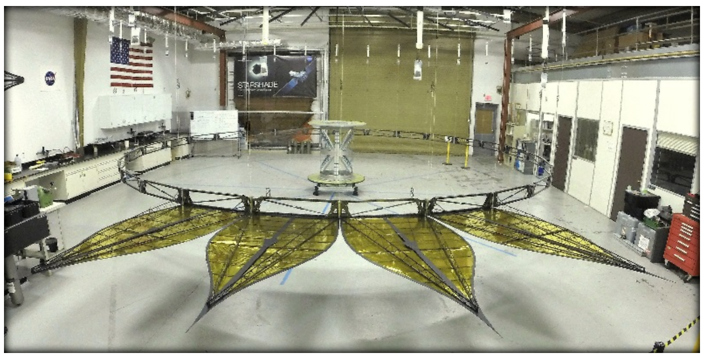
- 10m inner disk testbed was completed in 2014.
- 2m testbed completed for demonstrating origami shield designs in 2015.
- TDEM-14 awarded for optical shield design and integration into 10m inner disk testbed (Mark Thomson/JPL).

Inner Disk Prototype Deployment Trial at JPL

Optical Shield Prototype Deployment Trial at JPL

Inner Disk Deployment

Description	Current Capabilities	Needed 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 (Exo-S design).	Demonstrate deployment tolerances are met 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

- NGAS/JPL review of Exo-S design
- Integrate optical shield into 10m inner disk testbed (TDEM-14; FY16-17)
  - ❑ 5m optical shield testbed will allow larger prototype development (FY16)
- 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 in 2015.
- TDEM-14 awarded for optical shield design and integration into 10m inner disk testbed (Mark Thomson/JPL).

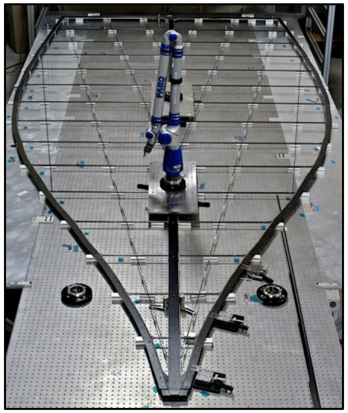
Petal Shape

Description	Current Capabilities	Needed 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 rms of shape tolerances and maintains shape after multiple deployments from stowed configuration.

Next Steps to Closing Technology Gap

Kasdin TDEM-12 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); not necessarily at some TRL but reduced risk by 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

Contrast vs Angular Separation

Exoplanet Exploration Program