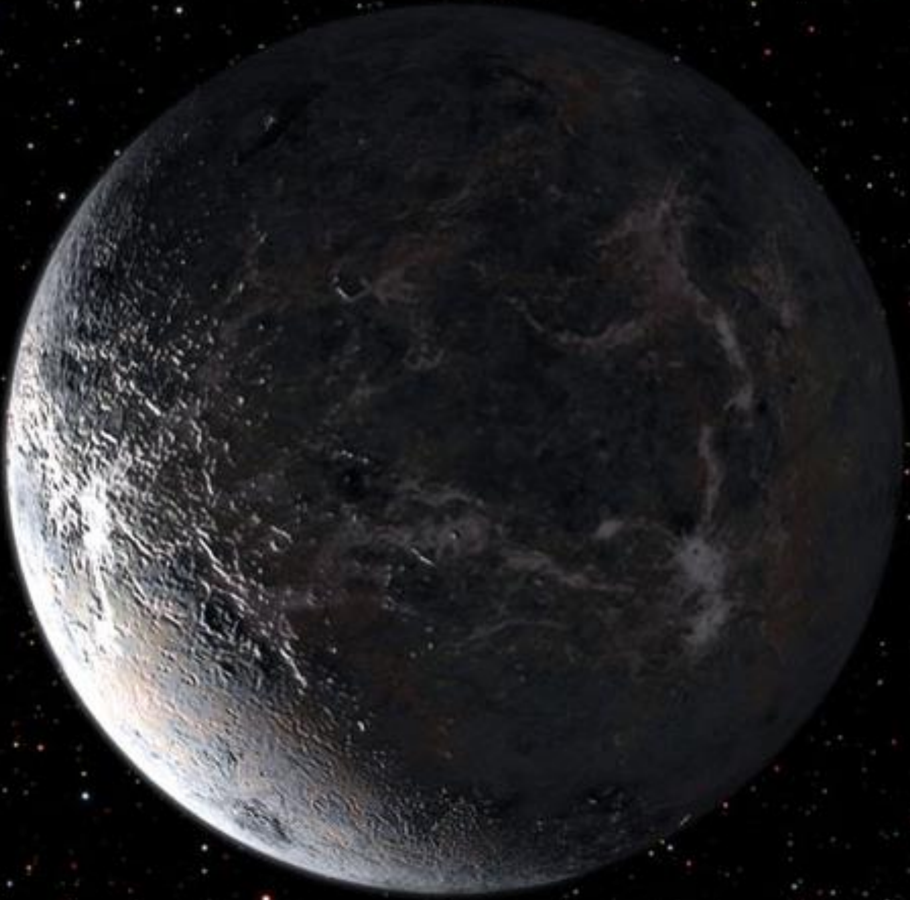
Jet Propulsion Laboratory
California Institute of Technology

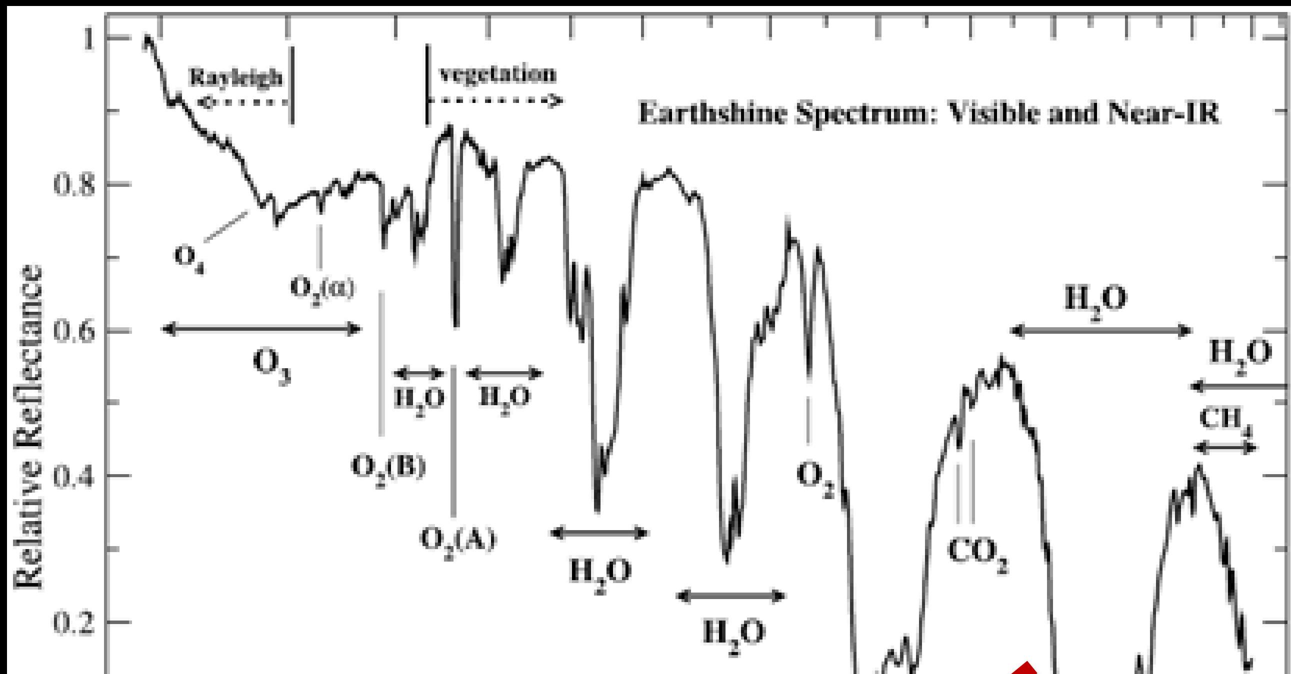
Mirror Technology Days Workshop
Annapolis, MD, November 2015

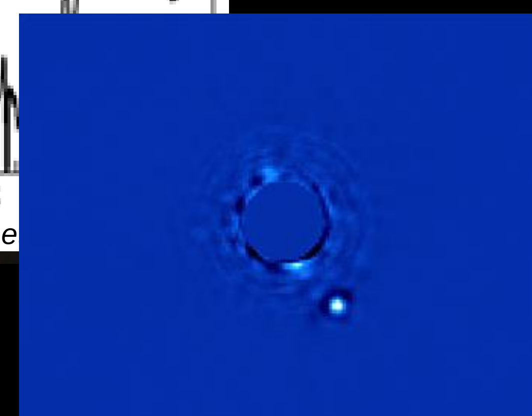
Exoplanet Exploration Program Technology Needs and Opportunities

Dr. Nick Siegler
Program Chief Technologist
NASA Exoplanet Exploration Program



Starlight Suppression is the Key Technology in the Search for Life on Earth-Size Exoplanets

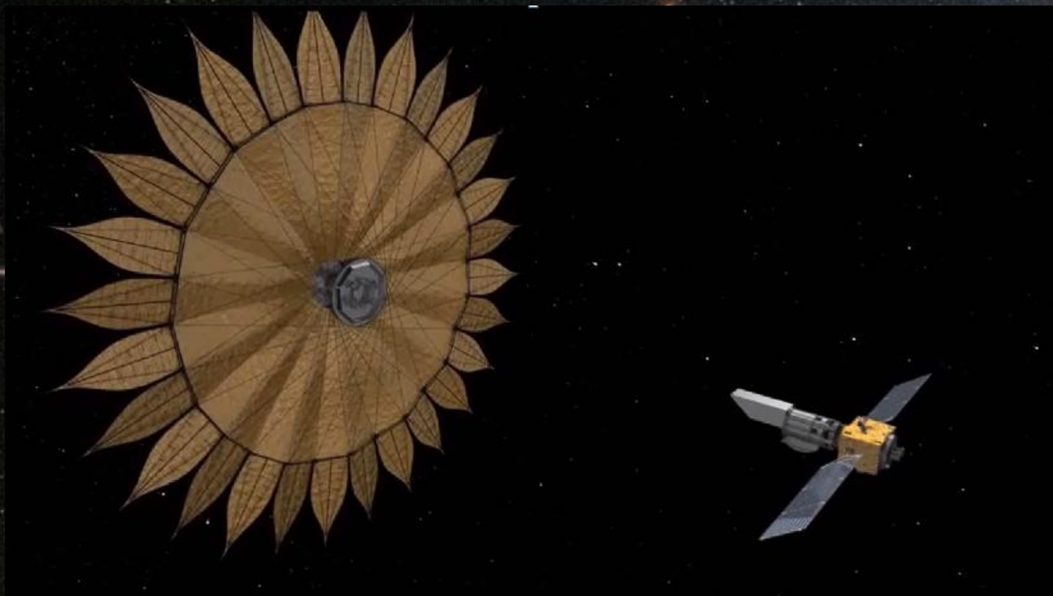


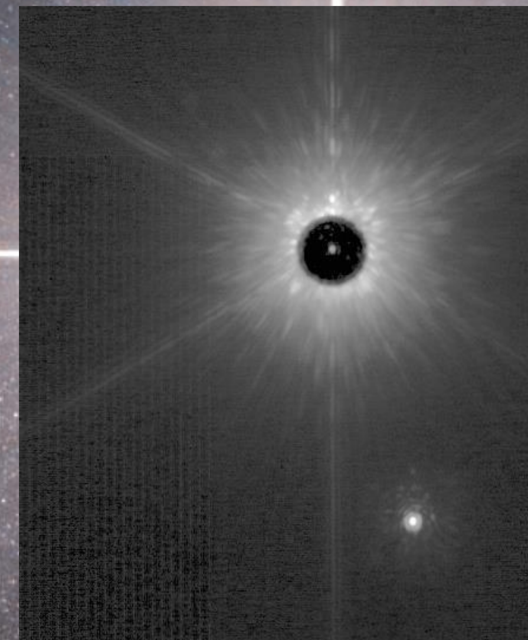


Macintosh et al. 2015

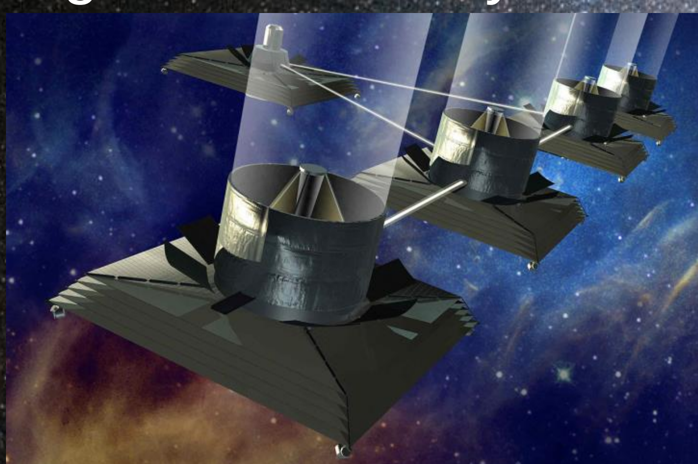
Enabling Starlight Suppression Technologies

External Occulters (Starshades)

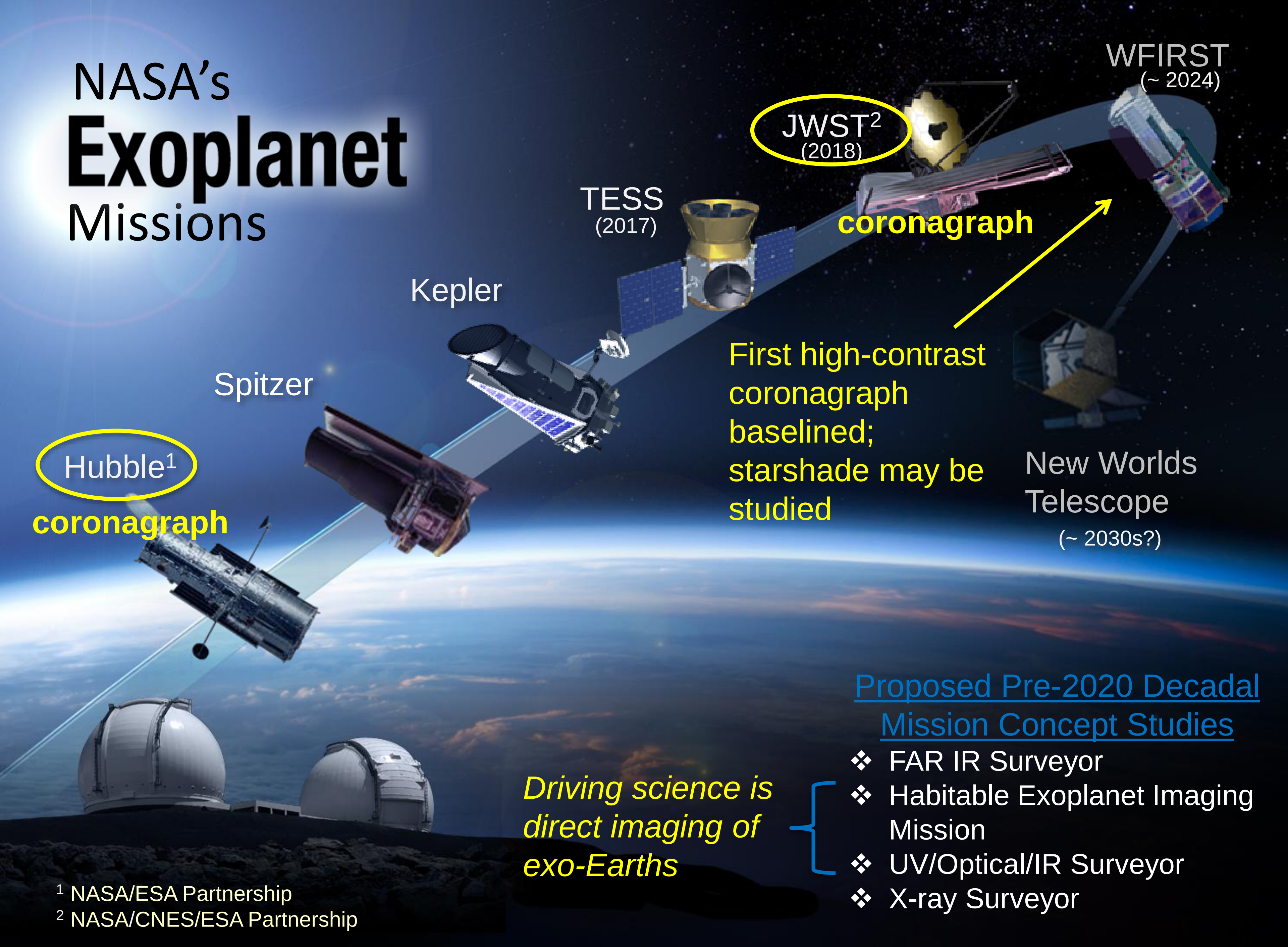




Nulling Interferometry

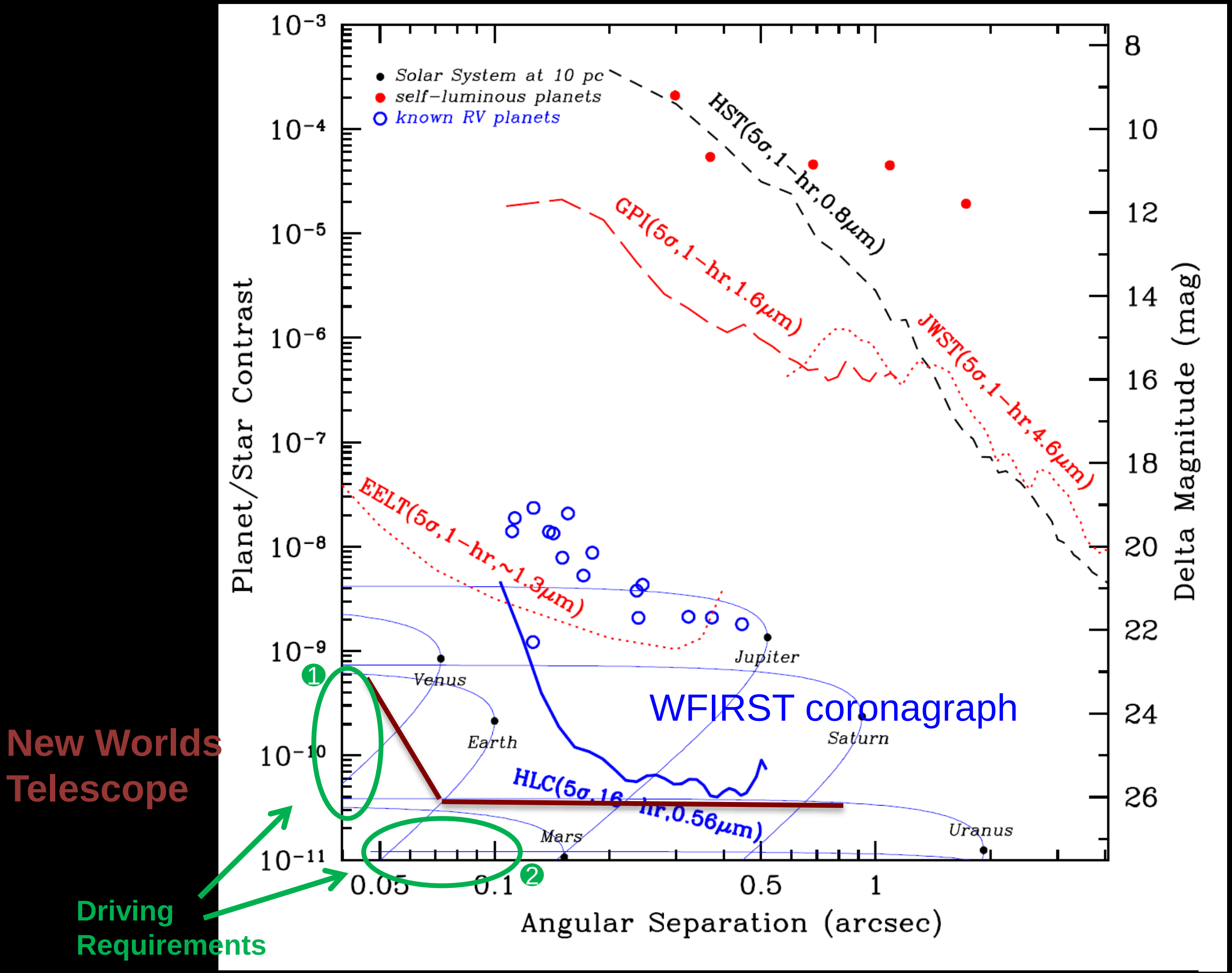


Internal Occulters (Coronagraphs)



NASA's
Exoplanet
Missions
WFIRST
(~ 2024)
JWST[2]
(2018)
TESS
(2017)
coronagraph
Kepler
First high-contrast coronagraph baselined; starshade may be studied
Spitzer
Hubble[1]
coronagraph
New Worlds Telescope
(~ 2030s?)
Proposed Pre-2020 Decadal Mission Concept Studies
❖ FAR IR Surveyor
❖ Habitable Exoplanet Imaging Mission
❖ UV/Optical/IR Surveyor
❖ X-ray Surveyor
Driving science is direct imaging of exo-Earths
[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership

Driving Requirements for Imaging Exo-Earths



Credit: Wes Traub

ExEP Technology Gap Lists

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 $\sim10^{-9}$ 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.

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

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.

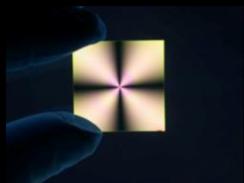
Next update in Jan 2016

See Morgan & Siegler SPIE 2015

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

Coronagraph Technology Needs

Starlight Suppression



Coronagraphy optics

Deformable mirrors

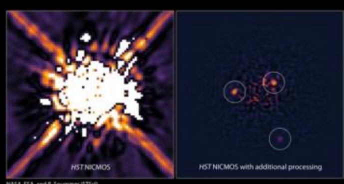
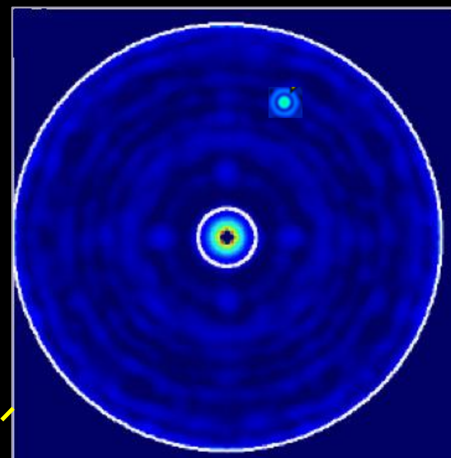
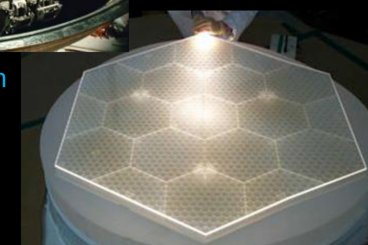


Image post-processing



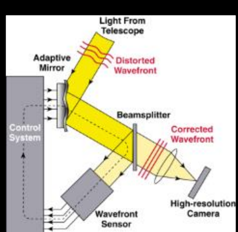
Angular Resolution

Large monolith



Segmented

Wavefront Stability

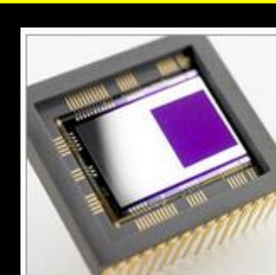


Low-order wavefront control

Segment phasing and rigid body control

Telescope vibration control

Detection Sensitivity

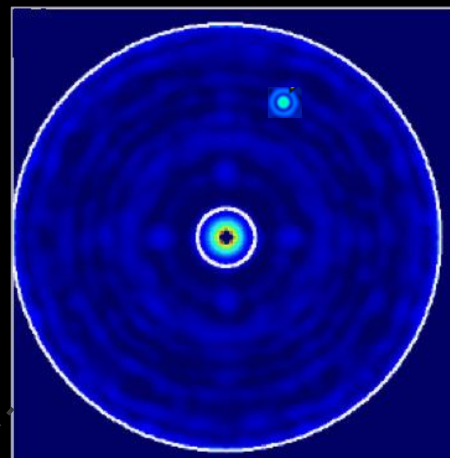


Ultra-low noise detectors
(visible and infrared wavelengths)

Coronagraph Technology Needs

Starlight Suppression

Angular Resolution

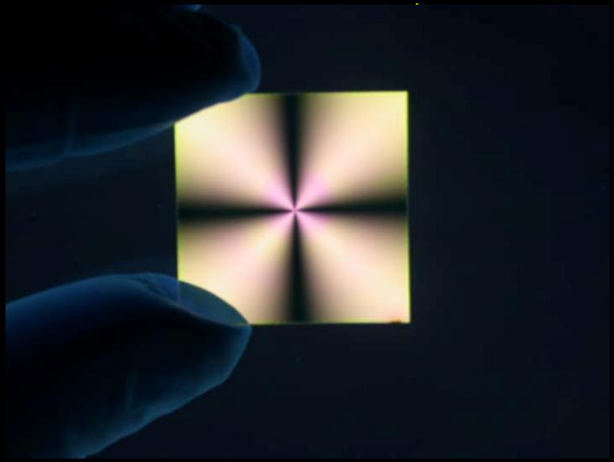


Detection Sensitivity

Wavefront Stability

Coronagraph Technology Needs

Starlight Suppression



Coronagraphy optics

Future Needs:

- Raw contrast < 10^{-9} (obscured and segmented)
- IWA ≤ 3 λ/D
- Bandwidth ≥ 10%

SOA:

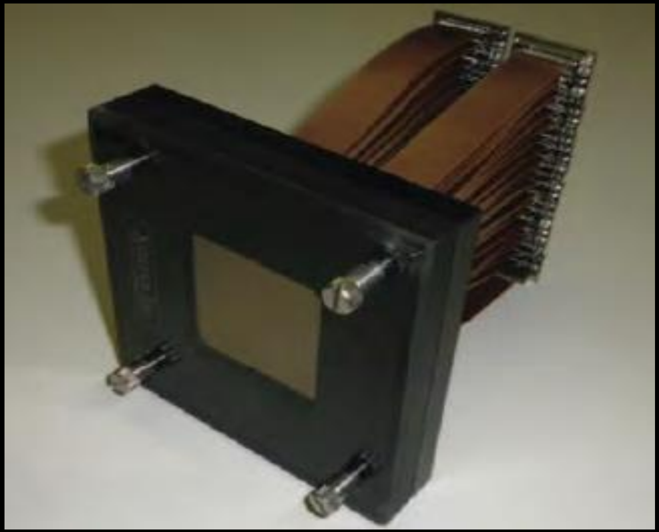
- WFIRST: Raw contrast: few x 10^{-9} (obscured); 3×10^{-10} (unobscured; Hybrid Lyot)
- IWA ~ 3 λ/D
- Bandwidth 10%

Current Activities:

- WFIRST coronagraphs planned to achieve TRL 5 by end FY16
- Additional demonstrations ongoing at STScI (APLC) and GSFC (VNC)
- ExEP planning FY16 design study to identify coronagraph architectures that can reach < 10^{-9} on large segmented apertures (FY16)
- Pre-Decadal mission concepts in FY16-18

Coronagraph Technology Needs

Starlight Suppression



Deformable mirrors
(Xinetics 48x48)

Need:

- ≥ 96x96 actuators
- radiation and env’t qualified
- flight electronics and connectors
- pitch sizes ≤ 1 mm
- stroke ≥ 500 um

SOA:

- 64x64 electrostrictive actuators by Xinetics (WFIRST baselined 48x48)
- 3×10^{-10} contrast achieved with 32x32
- pitch size = 1 mm
- stroke = 500 um

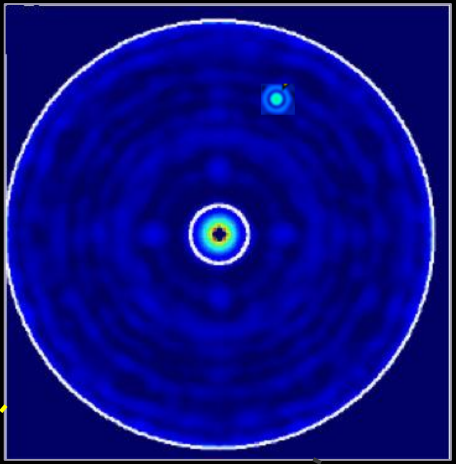
Current Activities:

- 48x48 Xinetics DMs are being flight qualified, connector study, flight electronics design (WFIRST; FY16-17)
- MEMS DMs (BMC and Iris AO) env’t testing (FY16-17)
- Pre-Decadal mission concepts in FY16-18

Coronagraph Technology Needs

Starlight Suppression

Angular Resolution

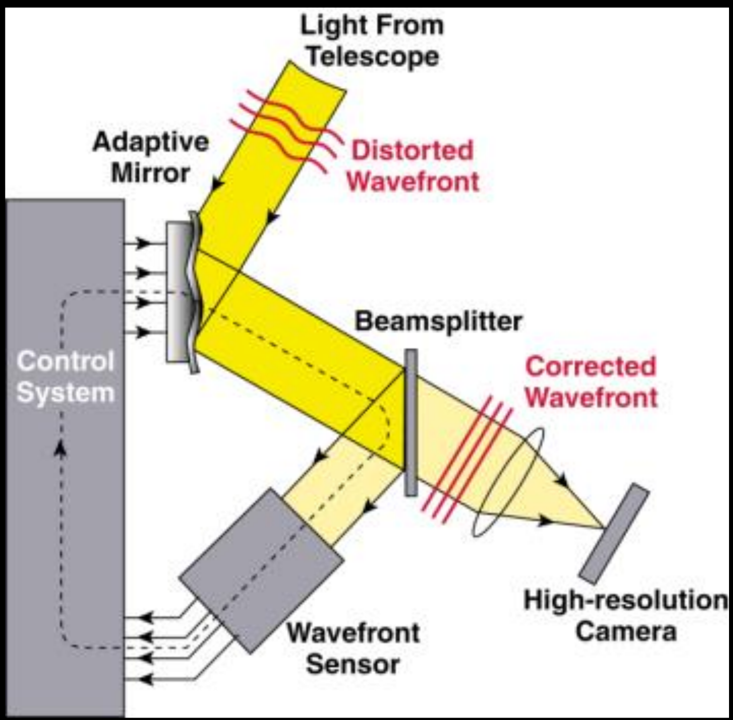


Detection Sensitivity

Wavefront Stability

Coronagraph Technology Needs

Wavefront Stability



Low-order wavefront sensing and control

Needs:

- Low-order WFE terms sensed and corrected to maintain 10^{-11} contrast stability
- < 10 pm rms uncorrected WFE

SOA:

- Zernike wavefront sensor baselined on WFIRST
  - 14 mas simulated jitter input (tip/tilt only) corrected to ≤ 0.5 mas rms residual

Current Activities:

- WFIRST LOWFS sensing first few modes to be demonstrated with a telescope and env’t simulator with a coronagraph (FY16)
- Pre-Decadal mission concepts in FY16-18

Coronagraph Technology Needs

Wavefront Stability

Segment phasing and rigid body control

Telescope vibration control

Needs:

- Segment phasing control to < 10 pm rms
- Disturbance: 140 dB at > 40 Hz

Relative to SOA:

- WF stability 2-3 OOM better than HST
- 1-2 OOM segment phasing and rigid body control (non-NASA); 3 OOM JWST
- 1 OOM in vibration control (WFIRST)
- Disturbance: 80 dB at > 40 Hz (JWST; passive)

Current Activities

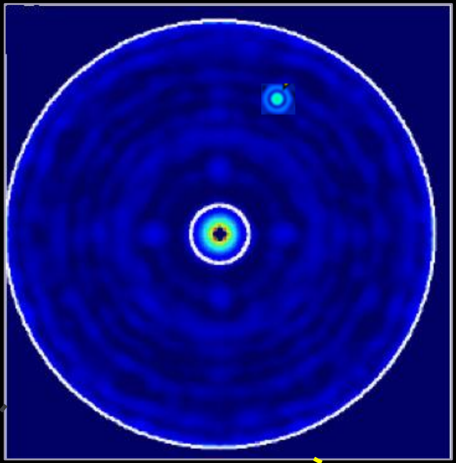
- Pre-Decadal mission concepts in FY16-18 to conduct key systems trade studies
    - segmented vs monolith primaries
    - active control vs passive vs hybrid for thermal, vibration, SFE

Note: can be relaxed to SOA for starshade

Coronagraph Technology Needs

Starlight Suppression

Angular Resolution



Detection Sensitivity

Wavefront Stability

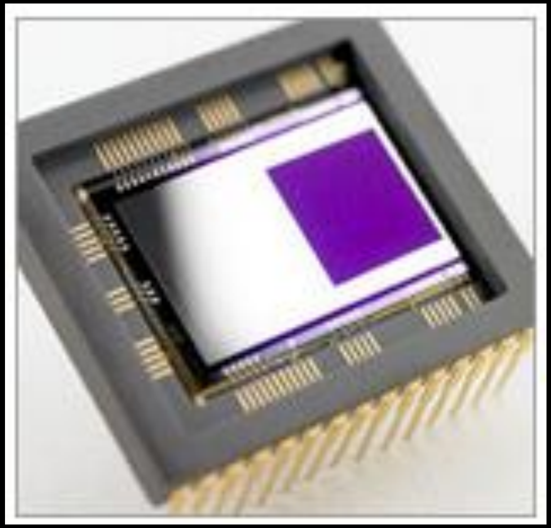
Coronagraph Technology Needs

Needs (Visible):
- 0.4 – 1 um ultra-low noise detectors
- Read noise: << 0.1 e'/pix
- Dark current: < 0.0001 e'/pix/s
- Format: > 2kx2k
- Radiation hard

Relative to SOA:
- 1kx1k EMCCD baselined for WFIRST
- OOM in RN and DC
- Not environmentally tested

Current Activities:
- Radiation testing (WFIRST; FY15-16)
- Flight R/O electronics design (WFIRST; FY16-18)
- Env't testing

Detection Sensitivity



e2V EMCCD 1kx1k

Coronagraph Technology Needs

Needs (IR):

- 1-5 um
- Read noise: < 1 e'/pix
- Dark current: < 0.001 e'/pix/s
- Format: arrays of ≥ 2kx2k
- Radiation hard
- Zero-vibration cooling

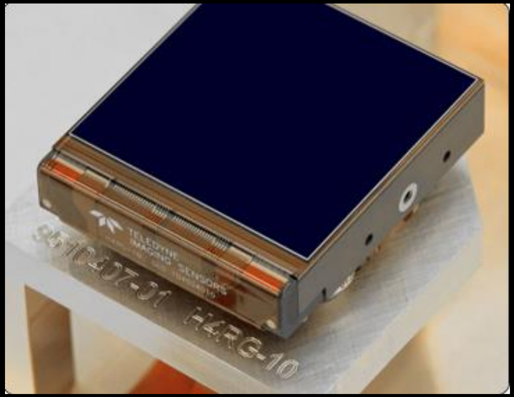
Relative to SOA:

- HgCdTe APD Hybrid
- Read noise: << 1 e'/pix
- Dark current: 10-20 e'/pix/s
- Format: arrays of < 1kx1k

Current Activities:

- HgCdTe (WFIRST) and APD noise reduction efforts
- MKIDS and TES are low-TRL cryo solutions
- Pre-Decadal mission concepts to determine long λ cutoff (FY16)

Detection Sensitivity



Teledyne H4RG-10 IR detector

	Technology	Visible 350 — 950 nm	Near-IR 950 nm — 5 μm	Mid-IR 5 μm — 8 μm
	CCD	Rad. hardness		
Baselined by WFIRST	CMOS			
→	EMCCD	Rad. hardness		
	p-channel CCD			
Being evaluated now	Si PIN Hybrid			
	HgCdTe Hybrid			
→	HgCdTe APD Hybrid	Reduce dark current	Reduce dark current	
Cryogenic detectors	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			

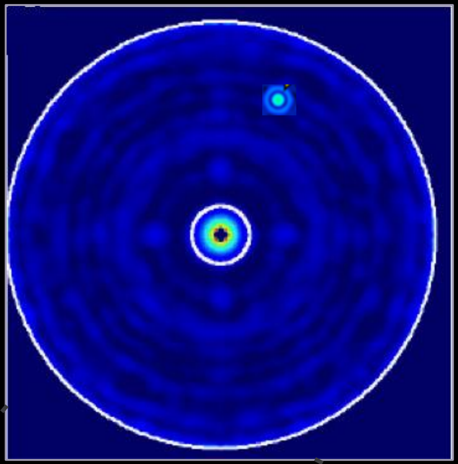
Green	TRL ≥ 6; Sufficiently mature for pre Phase-A
Blue	Promising technology, more work needed in specific area
Light blue	Promising technology
Grey	Cryogenic cooling required
Yellow	May be worth looking into with additional optimization

Rausch et al 2015 (SPIE)

Coronagraph Technology Needs

Starlight Suppression

Angular Resolution



+ increased sensitivity
+ higher throughput
+ shorter integration time
+ greater planet yield

Detection Sensitivity

Wavefront Stability

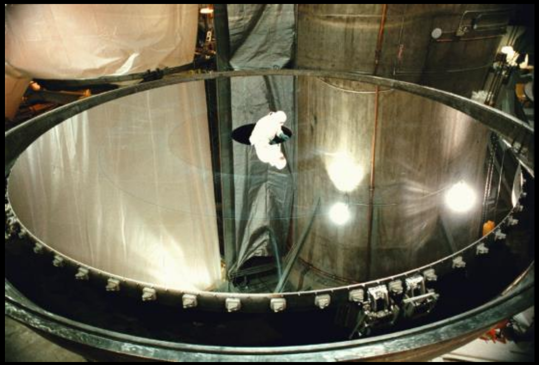
Coronagraph Technology Needs

Needs:
- ≥ 4m monoliths and ≥ 8m segmented mirrors
- SFE < 10 nm RMS
- Active thermal control; likely figure control for segments

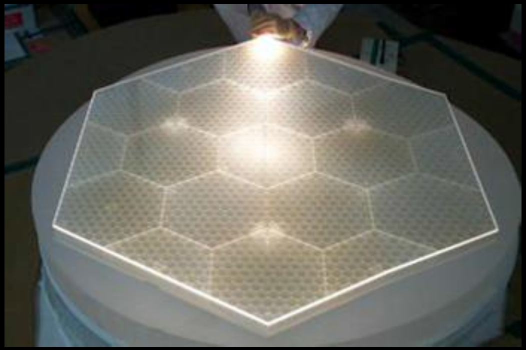
SOA:
- Monolith: HST’s 2.4m (~ 10 rms SFE)
- Segmented: JWST’s 6.5m (18 segments, 1.3m)
- SFE: < 30 nm RMS

Current Activities:
- Non-NASA investments
- Pre-Decadal mission concepts will study monolith vs segments, materials, active figure control

Angular Resolution



Large monolith
(Gemini 8.1m ULE)

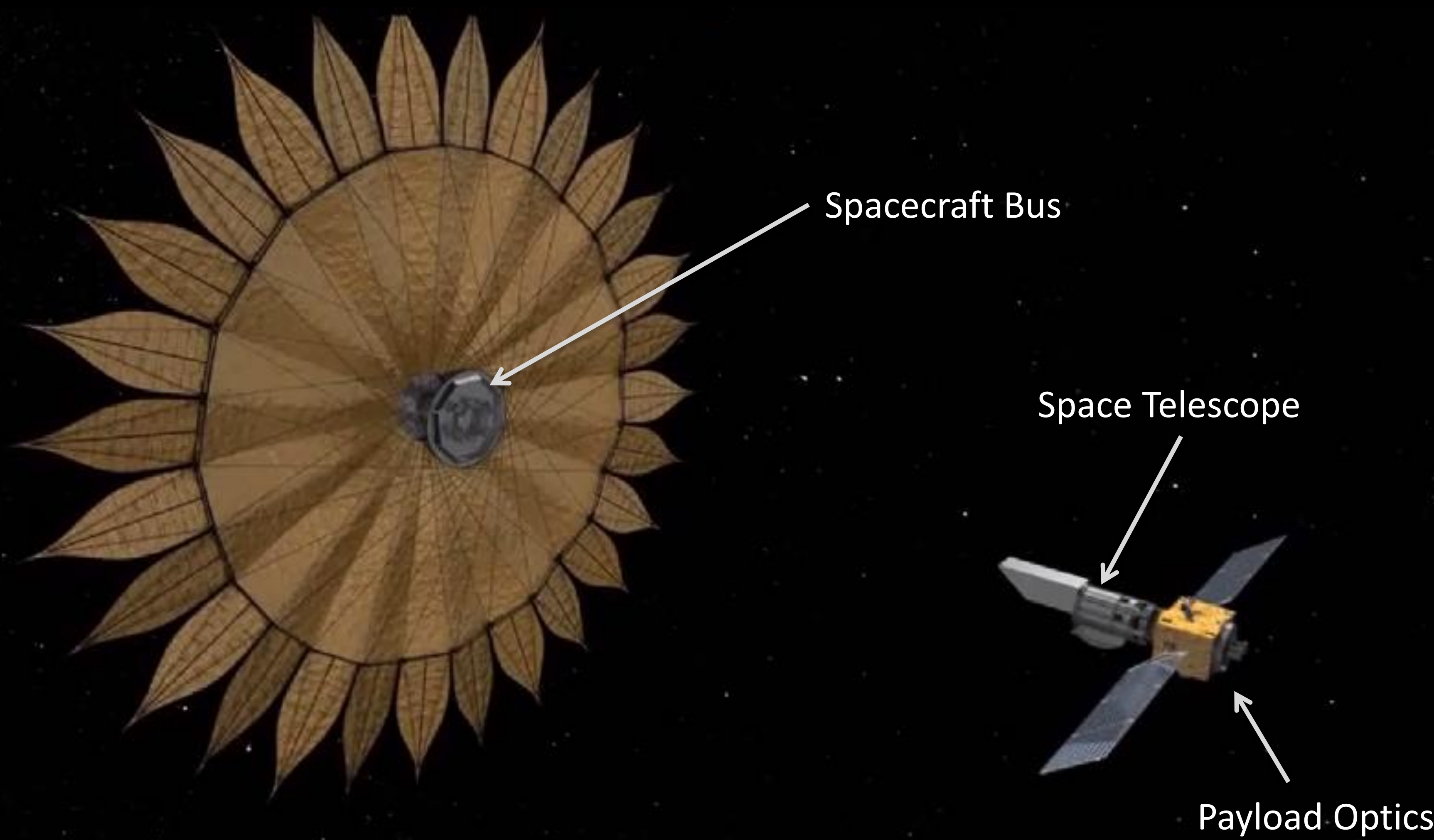


Segmented
(AMSD lightweighted ULE Segment; ITT)

Segmented
AHM SiC-based Segment, Xinetics

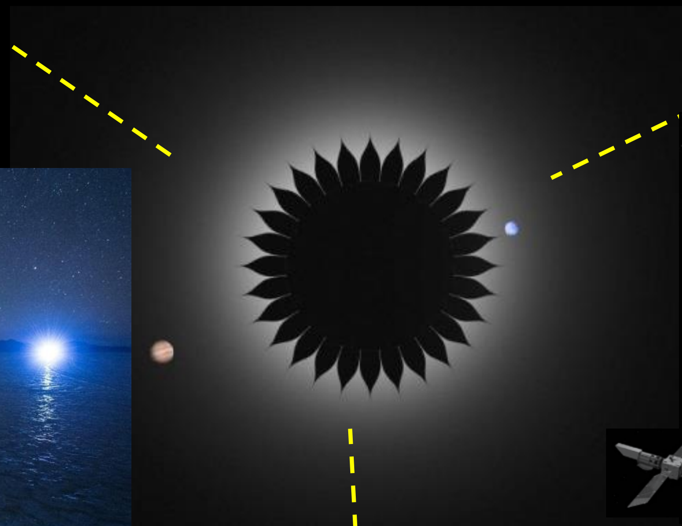
Starshade Technology Needs

What's not hard…

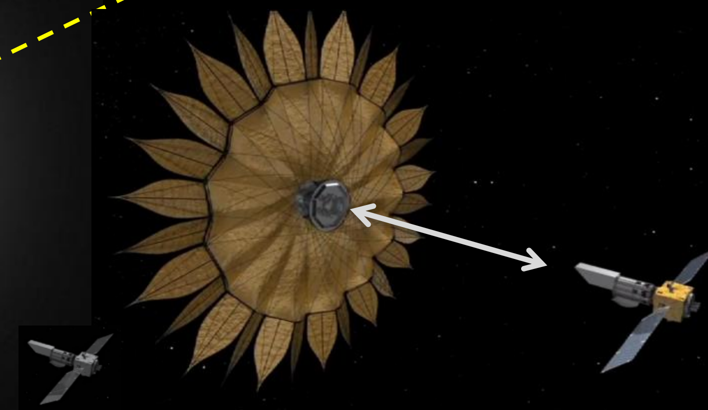


Starshade Technology Needs

Diffraction and Scattered Light Control



Lateral Formation Flying Sensing

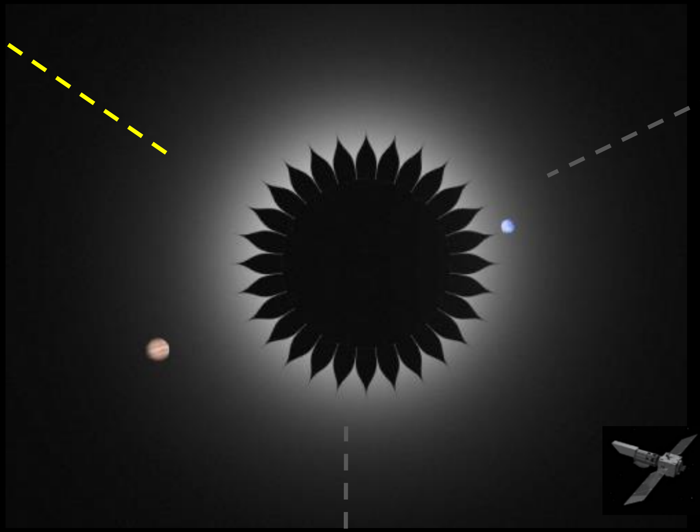


Large Deployable Structures

Starshade Technology Needs

Diffraction and Scattered Light Control

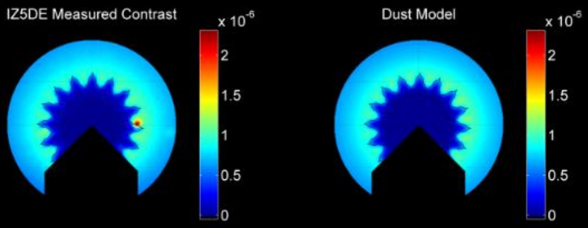
Lateral Formation Flying Sensing



Large Deployed Structures

Starshade Technology Needs

Diffraction and Scattered Light Control



Needs:

- Contrast ≤ 10^{-10} demonstrated near the petal edges at a flight Fresnel number
- Optical model validation
- Optical edge material identified and integrated to a full-scale petal

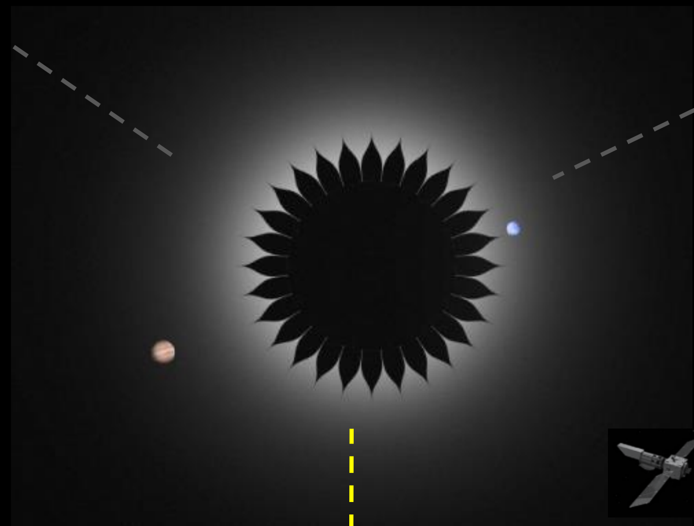
Current Activities:

- Optical performance and modeling studies (Princeton/JPL, NGAS, Colorado/JPL) – FY16-18
- Optical edge studies (NGAS, JPL) – FY16-17

Starshade Technology Needs

Diffraction and Scattered Light Control

Lateral Formation Flying Sensing



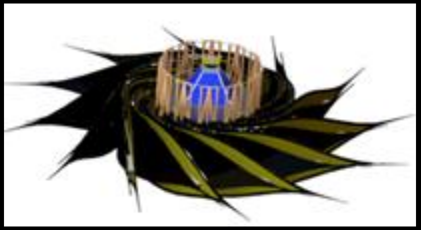
Large Deployed Structures

Starshade Technology Needs

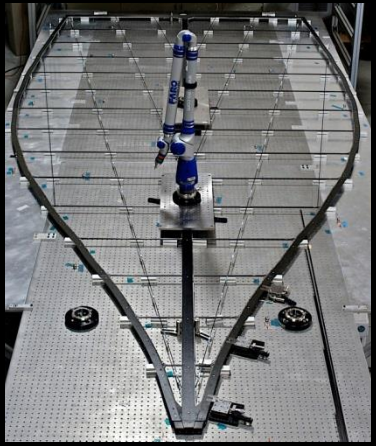
Large Deployable Structures

Half-scale inner disk testbed (JPL)

1/10-scale opaque membrane testbed (JPL)



Petal unfurling concept (Roccor)



6m petal (Princeton/JPL)

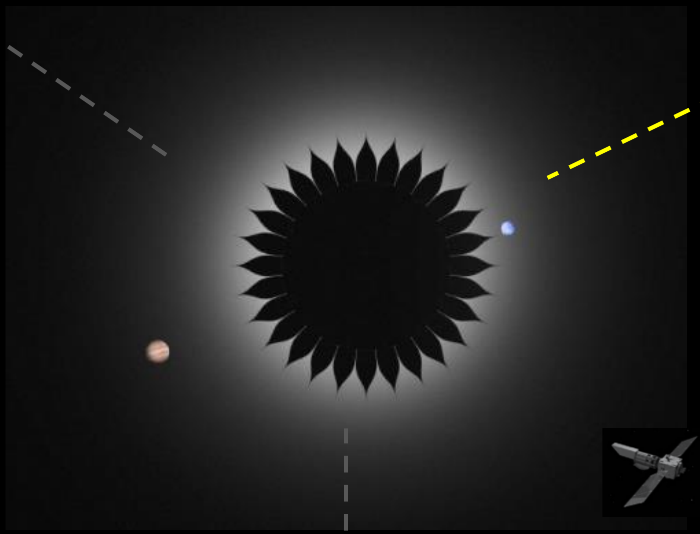
Needs:

- Full-scale (~ 7m) petal with flight-like materials that meet manufacturing tolerances (< 70 um).
  - ➢ FY16-17 (Princeton/JPL)
- Half-scale (10m) inner disk prototype with flight-like components and opaque membrane that meets deployment tolerances (< 0.45 mm).
  - ➢ FY16-17 (JPL)
- Full-scale petal latching and unfurling mechanism verifying no edge contact during launch and petal unfurling
  - ➢ FY16-18 (Roccor/JPL)
- 80m-class starshades designs? (TBD)

Starshade Technology Needs

Diffraction and Scattered Light Control

Lateral Formation Flying Sensing



Large Deployed Structures

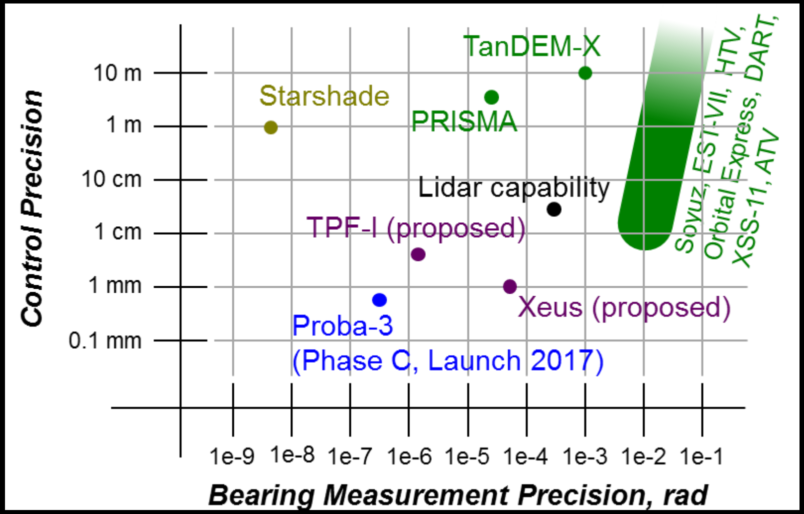
Starshade Technology Needs

Needs:

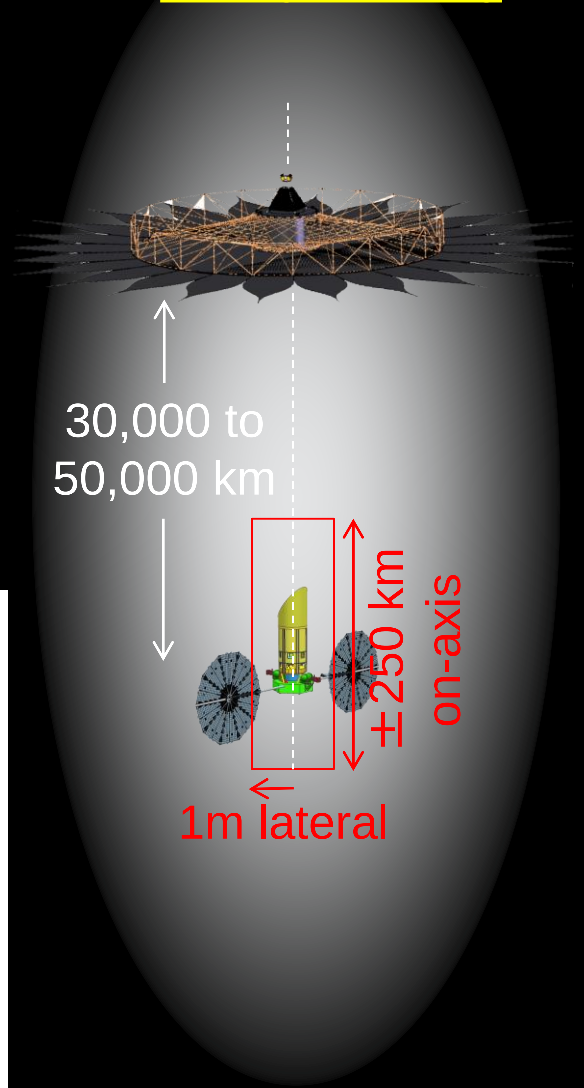
- Sense relative lateral offsets between telescope and starshade to within ± 20 cm at 50,000 km distance
    - Measure bearing angle to within ± 1.25 mas

Current Activities:

- Demonstrating mas bearing sensitivity with feedback control in scaled testbeds
    - Princeton/JPL, Colorado (FY16-17)



Lateral Formation Flying Sensing



Opportunities to Participate

- Engage with the ExoPAG (Program Analysis Group) – the exoplanet community group (http://exep.jpl.nasa.gov/exopag/)

- Consider investing/collaborating your own internal R&D funding targeted to one of our technology needs

- Propose for a Small Business Innovation Research (SBIR) grant
  - All ExEP technology gaps are mapped to the 2015 NASA Technology Roadmaps
    - http://www.nasa.gov/offices/oct/home/roadmaps/index.html

- Propose for a Technology Development for Exoplanet Missions (TDEM)
  - TRL 3-5 (http://nspires.nasaprs.com/external/)

- Propose for an Astrophysics Research and Analysis (APRA) grant
  - TRL 1-2 (http://nspires.nasaprs.com/external/)

- Visit the Exoplanet Exploration Program (ExEP) website
  - http://exep.jpl.nasa.gov/

- Contact me directly: nsiegler@jpl.nasa.gov

Further Reading

- P. R. Lawson, N. Siegler, B. Lim. “Exoplanet Exploration Program Technology Plan Appendix: 2015,” Jet Propulsion Laboratory, http://exep.jpl.nasa.gov/technology/
- Exo-S Final Probe Study Report *(best systems report on a potential starshade mission);* http://exep.jpl.nasa.gov/STDT
- Exo-C Final Probe Study Report *(recent probe-class study on an off-axis 1.4m monolith with a coronagraph);* http://exep.jpl.nasa.gov/STDT
- Bolcar et al. 2015 *(SPIE; good overview of the technology needs for a LUVOIR mission concept)*
- Morgan & Siegler 2015 *(SPIE; overview of the coronagraph technology needs for an exo-earth imaging mission)*
- W. A. Traub and B. R. Oppenheimer, “Direct Imaging of Exoplanets,” in Exoplanets, S. Seager ed. (University of Arizona Press: Tucson AZ, 2010) *(good technical paper on the challenges of imaging exo-earths)*

Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration