Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology Overview

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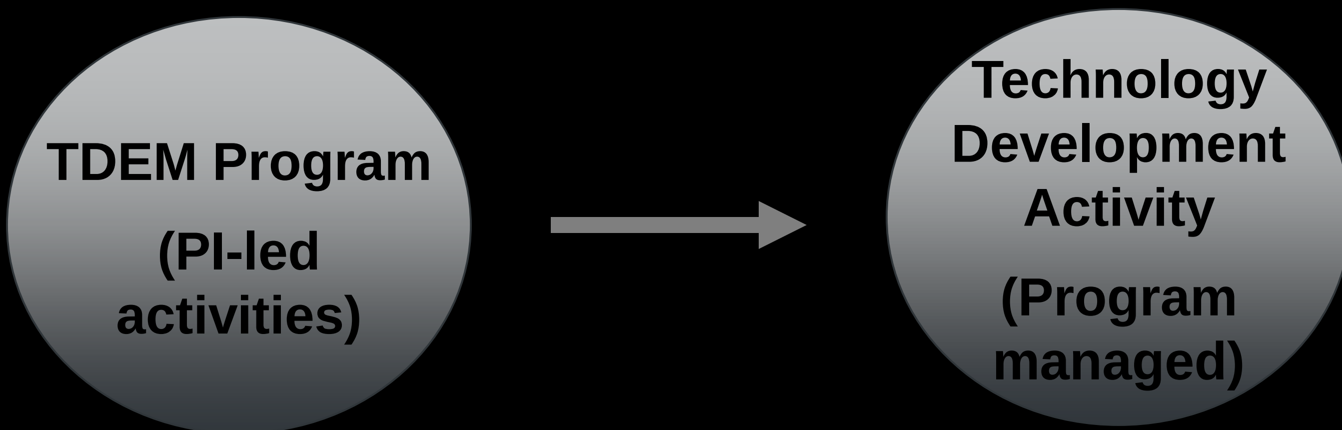
NASA Exoplanet Exploration Program
Jet Propulsion Laboratory, California Institute of Technology

Starshade Technology Workshop
December 1, 2016
Pasadena CA

CL#16-5718

March 2016:
Starshade Technology Development Activity Chartered



Component/Sub-system focus

System-focus

- Interface definitions
- System error budget and allocations
- Technical trades
- Scaling issues
- Reference mission (WFIRST)
- Lead NASA center is JPL
- Primary funding source

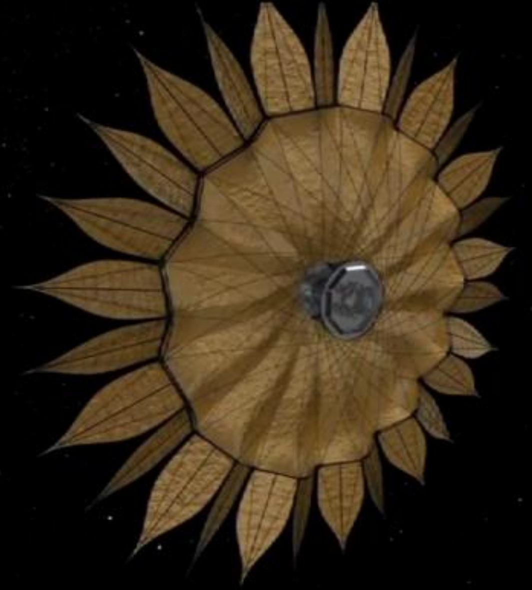
Key Goals and Deliverables of the Starshade Technology Activity

- Advance the technology readiness of the starshade to TRL-5
  - By end CY17:
    - TRL 5 Technology Development Plan
    - TRL 5 success criteria (vetted by an external review board)
    - key milestones with verification approaches
    - high-confidence cost and schedule estimates
    - key trade studies
    - preliminary designs for remaining test articles and testbeds
    - high fidelity error budget and key requirements
- Describe path to TRL-6 (PDR)

POC: John Ziemer (JPL)

May 2016:
Starshade Accommodation Added to WFIRST DRM

- WFIRST is assessing the impact of accommodating a potential future starshade mission
  - *First assessment briefing to NASA this month*
  - *Final decision no later than summer of 2017*



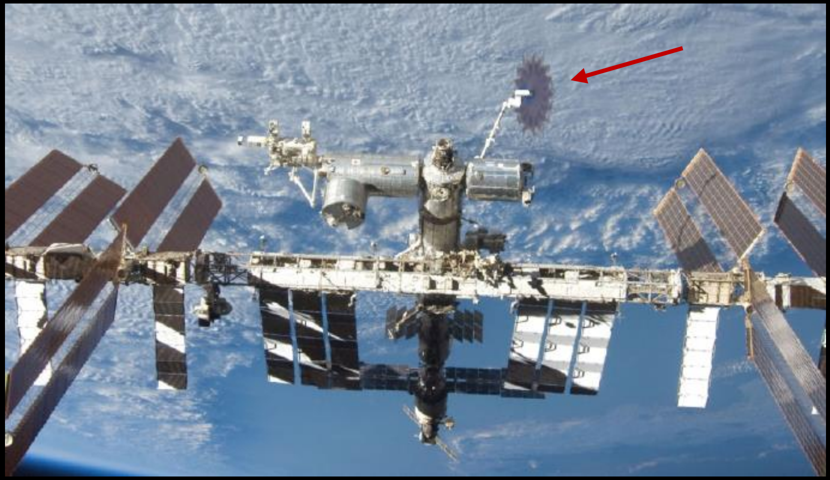
POC: Missie Vess (GSFC), John Ziemer/Doug Lisman (JPL)

November 2016:
Starshade Readiness Working Group Concludes

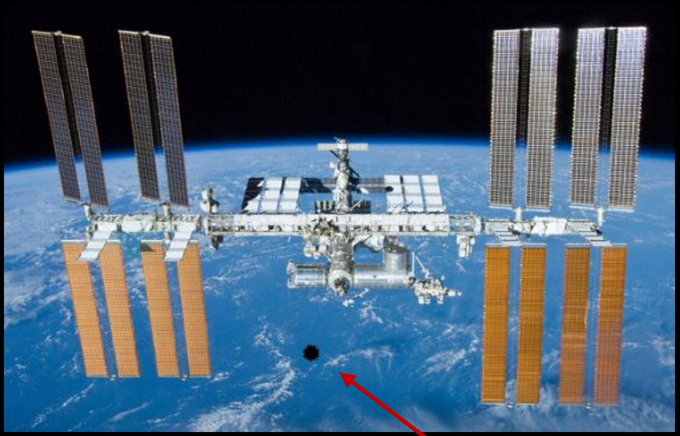
- Chartered with determining the path to flight, and if a space demonstration was required
- Included more than 30 participants from industry, academia, and multiple NASA centers
- Concluded a ground-based technology development program would be sufficient
  - *Briefed NASA in November*
    - *https://exoplanets.nasa.gov/exep/studies/sswg/*
  - *AAS Splinter Session*

POC: Co-Chairs: Gary Blackwood (ExEP) and Sara Seager (MIT)

Starshade Readiness Working Group



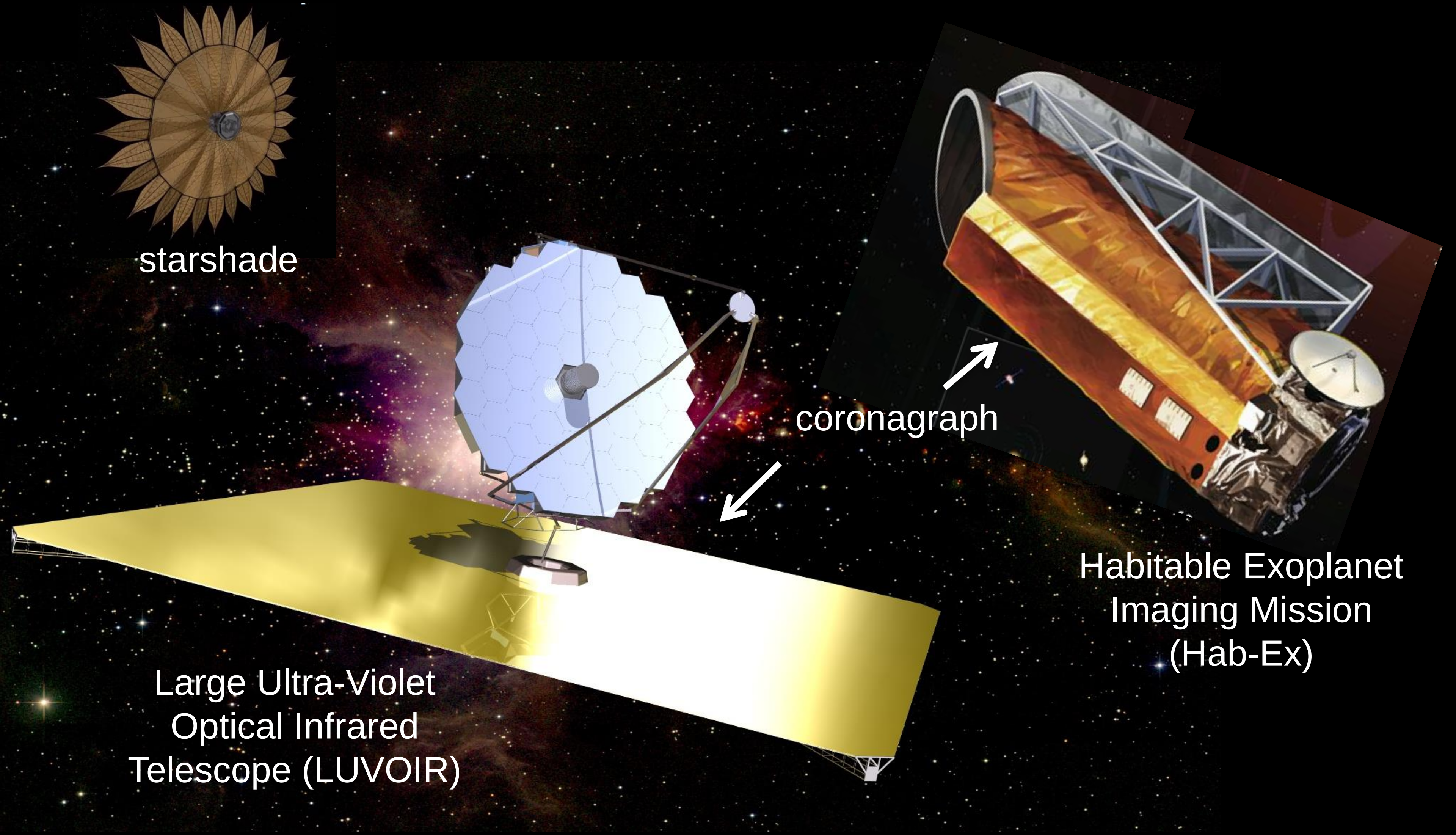
POC: Steve Warwick (NGAS)



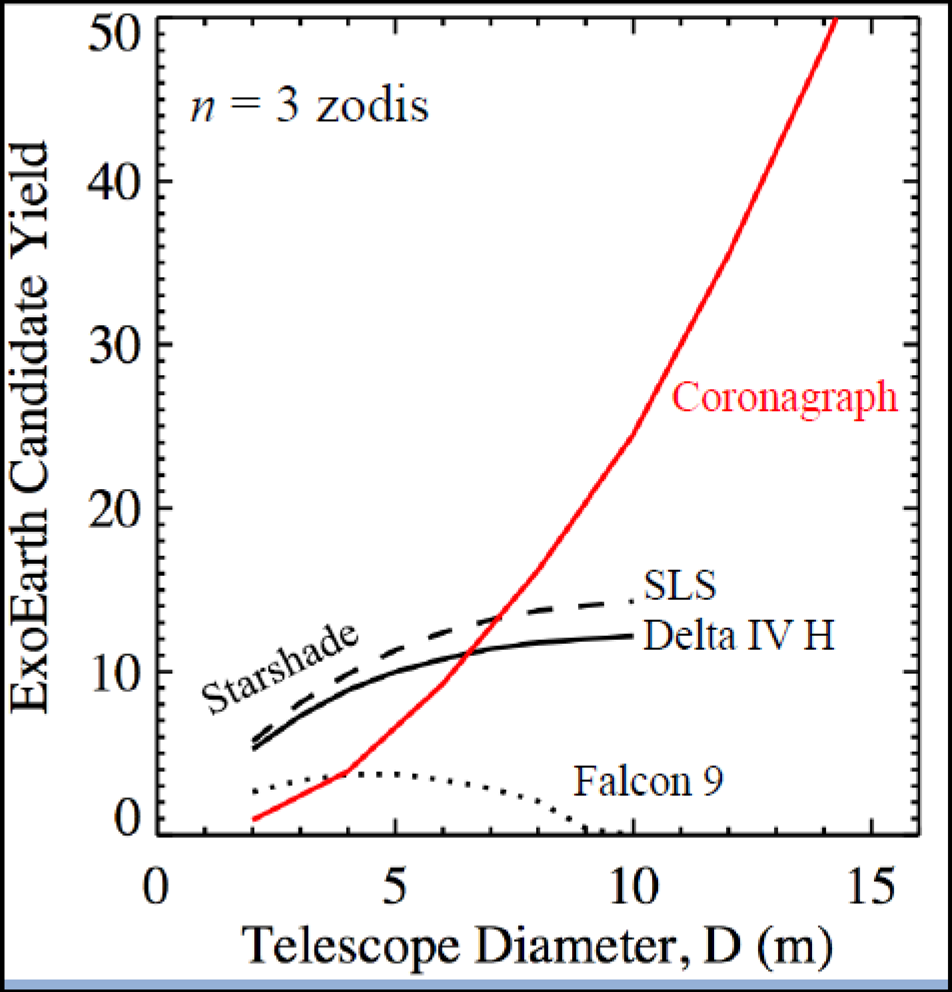
POC: Charley Noecker (JPL)

- 8 different options assessed including:
  - four flight demonstrations
  - two long ground baseline demo's
  - two ground demo's addressing all technology issues
- Options put forth separately by NGAS and JPL showed ground development paths to TRL-6 that addressed the three technology areas
- Stanford mDOT (PI D'Amico; flight demo) recognized as enhancing formation flying sensing and control along with optical performance but at additional costs and risk

Ongoing:
Next Generation Exo-Planet Mission Studies



Next Generation Exo-Planet Mission Studies

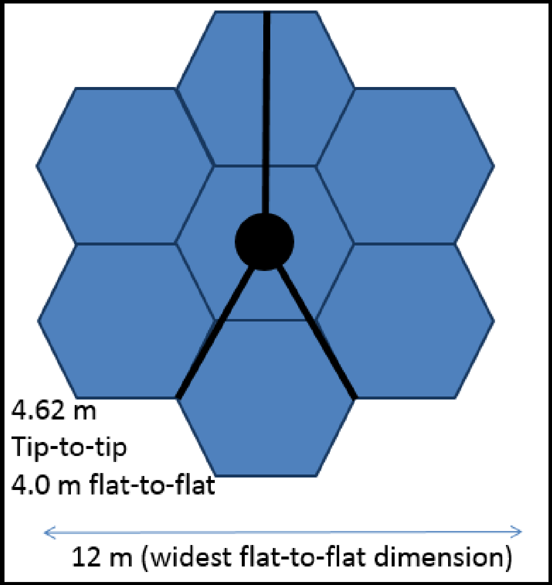


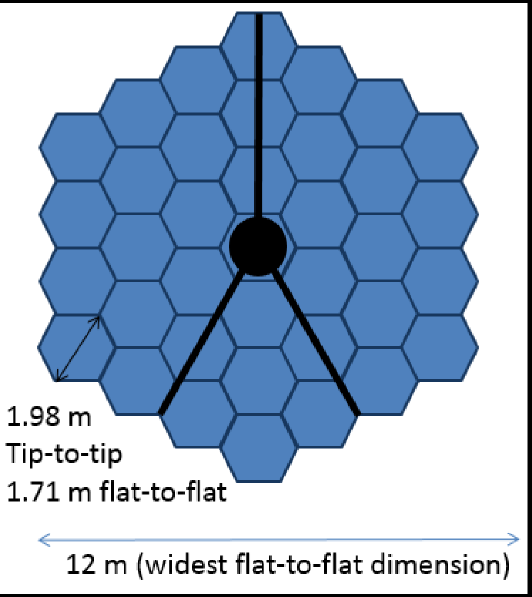
Chris Stark et al 2016

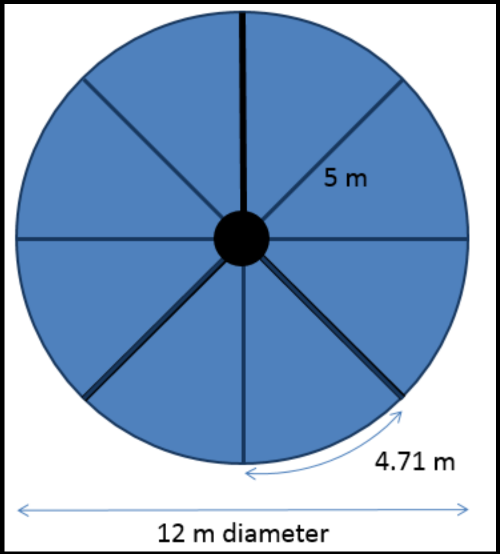
Starshades appear to outperform coronagraphs for telescope apertures less than 6 m

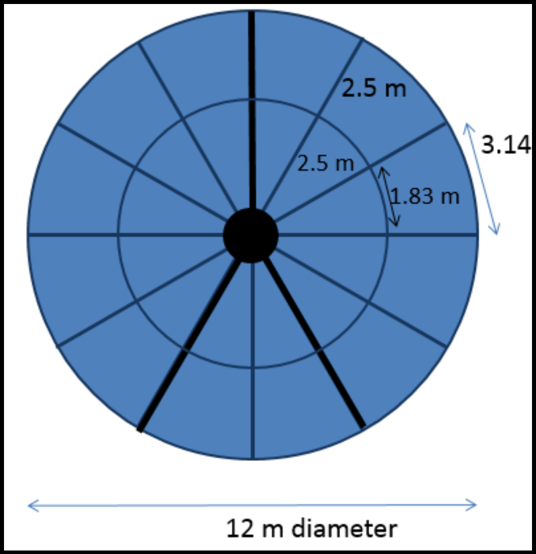
Next Generation Exo-Planet Mission Studies

ExEP Segmented Coronagraph Design and Analysis Study









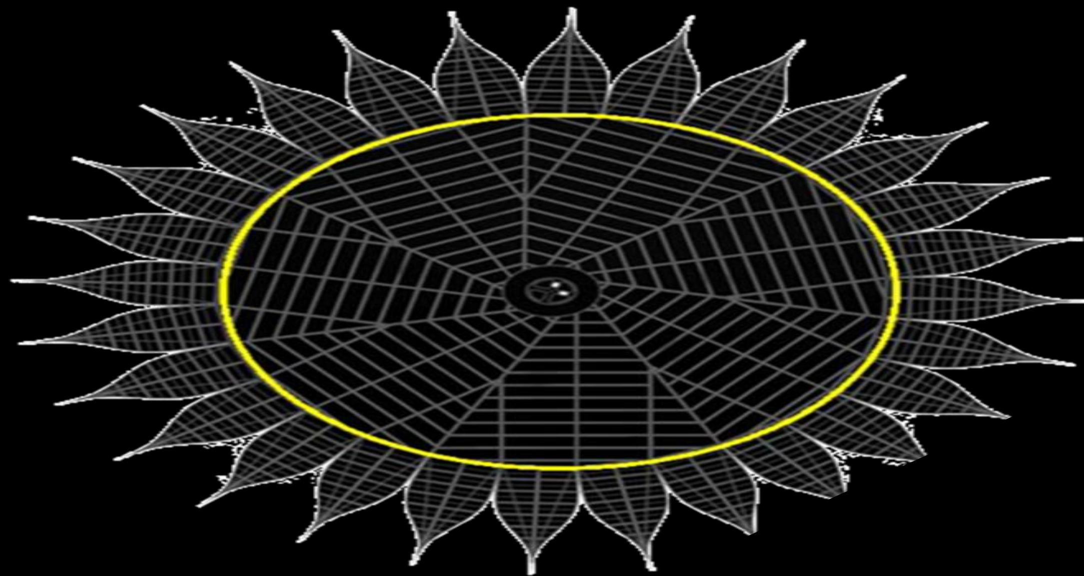
In search of coronagraph designs capable of achieving 10^{-10} contrast with large segmented telescope primary mirrors

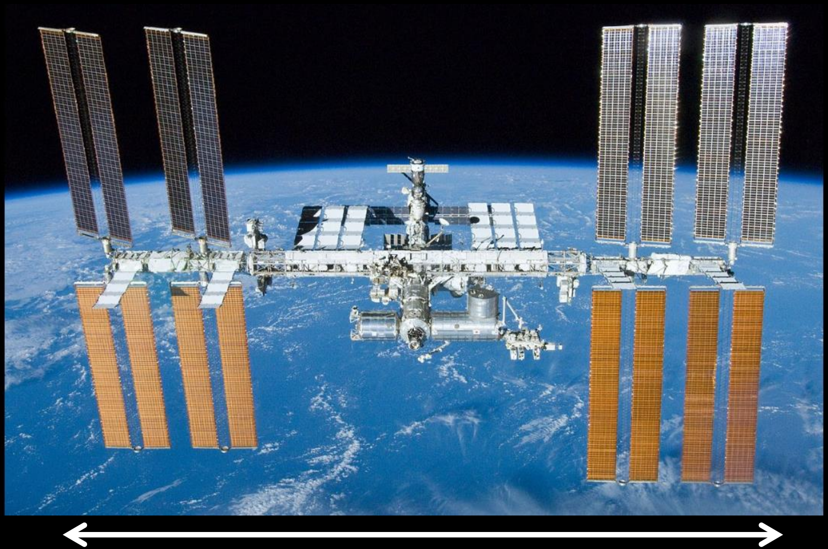
Will require 1-2 OOM improvement over SOA in both contrast and wavefront/structural stability.

Starshades do not have the same diffraction removal and wavefront stability challenges

POC: Stuart Shaklan (JPL)

100m-class Starshades?



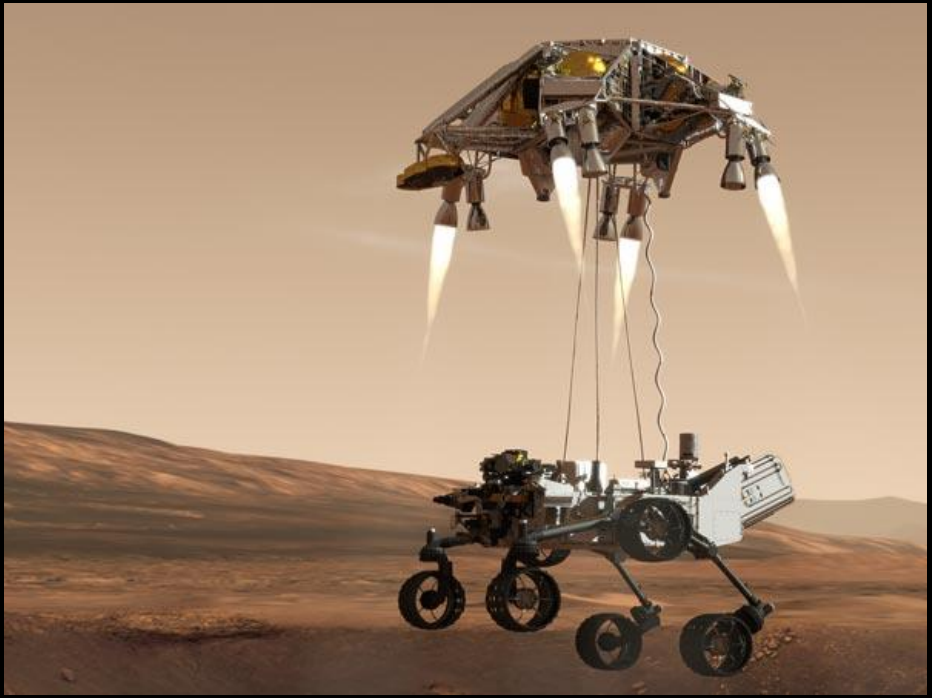


73 m

Pathfinder, Mars Exploration Rovers

1st generation
(Air Bags)

Curiosity Rover



2nd generation
(Sky Crane)

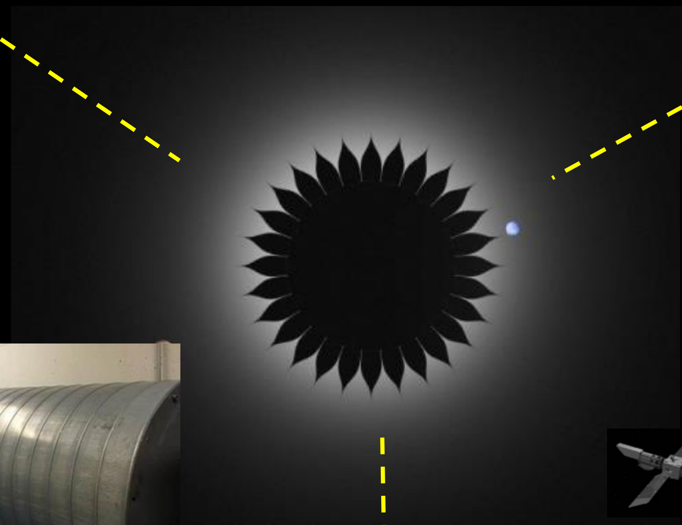
Starshade deployment architectures should be informed by long-term applications but not constrained.

Starshade Technology Needs

Three Key Technology Areas for Starshades

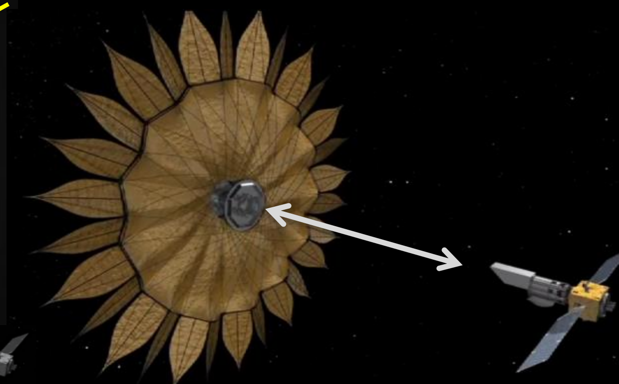
(1) Starlight Suppression

Suppressing scatted light off petal edges from off-axis Sunlight



Suppressing diffracted light from on-axis starlight

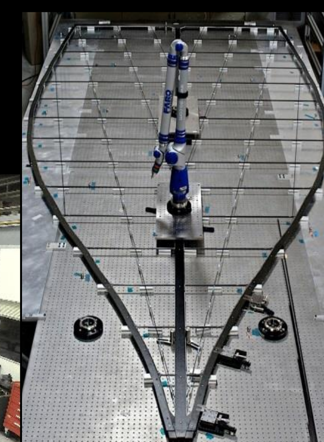
(3) Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts

(2) Deployment Accuracy and Shape Stability

Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure

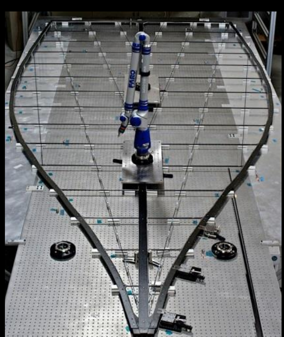


Fabricating the petals to high accuracy

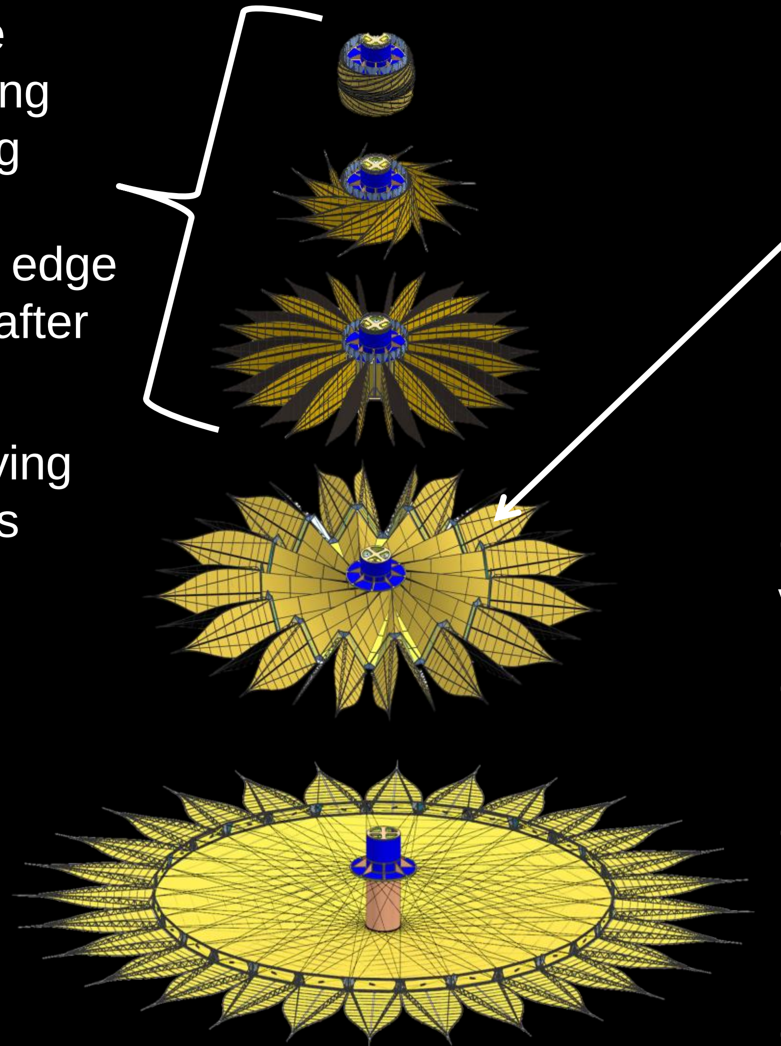
A Possible TRL-5 End State for a Starshade

(2) half- to full-scale latching and unfolding mechanism verifying controlled petal deployment with no edge contact during and after launch

(1) full-scale petal verifying optical shape tolerances and edge scatter performance



(4) Sub-scale test demonstrating lateral formation sensing accuracy



(3) half- to full-scale deployment and petal positioning mechanisms

Note: the deployment architecture remains an open trade at this time

Key models and analyses predicting:

(5) Optical performance and validated optical model

(6) Maximum micro-meteoroid hole area

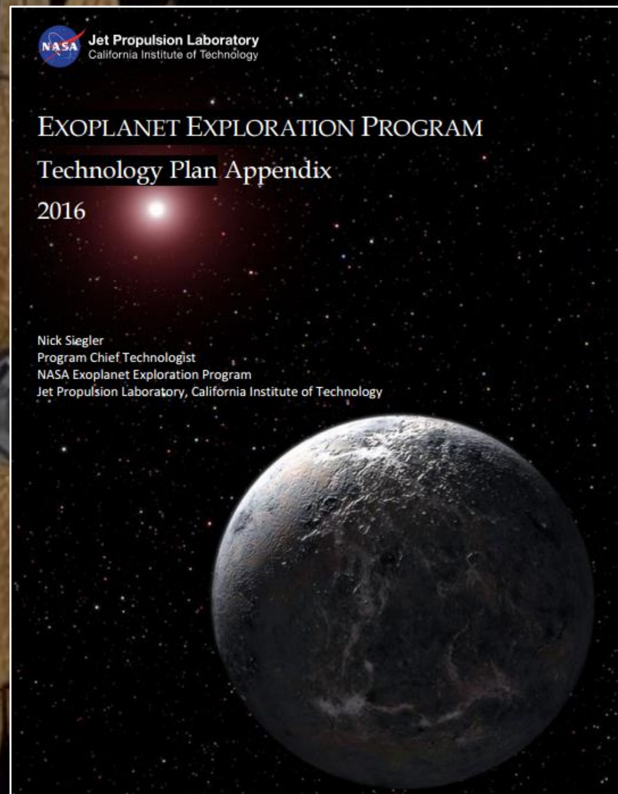
(7) Error budget and draft requirements for a possible mission concept

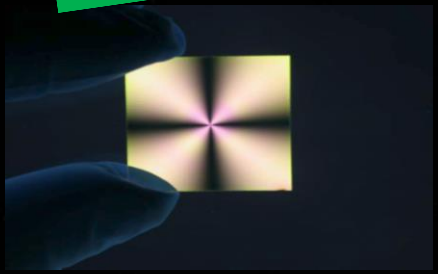
(8) Dynamic and thermal stability modeling

Path to TRL-6

2017 ExEP Technology Plan Appendix

To be updated and posted by end of month





Starshade 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 ≤ 3×10^{-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.

Coronagraph/Telescope 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 ≤ 1×10^{-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 ≤ 1×10^{-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 ≤ 10^{-9} contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to ≤ 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.

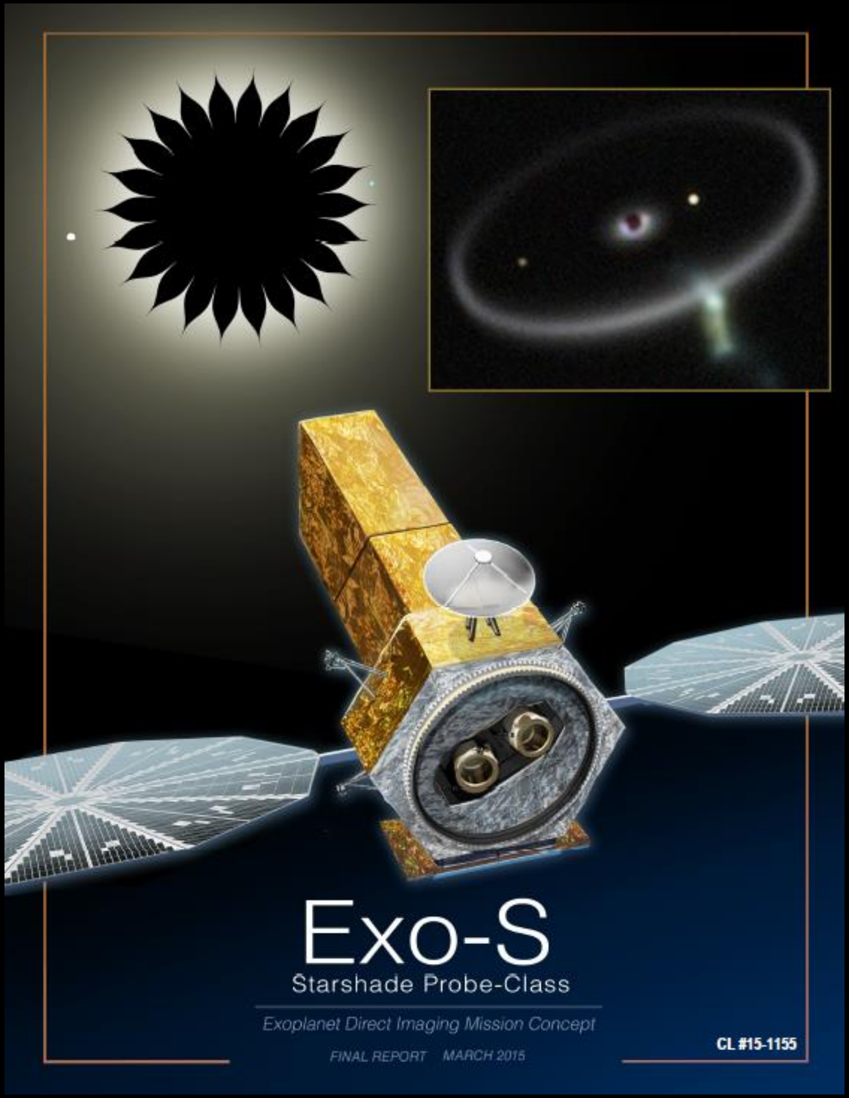
*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

http://exoplanets.nasa.gov/exep/technology/gap-lists/

Exo-S Study (2015)

Sara Seager, Chair (MIT)
W. Cash (U. Colorado)
S. Domagal-Goldman (NASA-GSFC)
N. J. Kasdin (Princeton U.)
M. Kuchner (NASA-GSFC)
A. Roberge (NASA-GSFC)
S. Shaklan (NASA-JPL)
W. Sparks (STSci)
M. Thomson (NASA-JPL)
M. Turnbull (GSI)

JPL Design Team:
K. Warfield, Lead
D. Lisman
R. Baran
R. Bauman
E. Cady
C. Heneghan
S. Martin
D. Scharf
R. Trabert
D. Webb
P. Zarifian



http://exoplanets.nasa.gov/exep/studies/

Starshade Technology Progress in 2016

5 m Origami Optical Shield Deployment Trial

POC: David Webb (JPL)

5 m Origami Optical Shield Deployment Trial

(approaching flight-like materials)

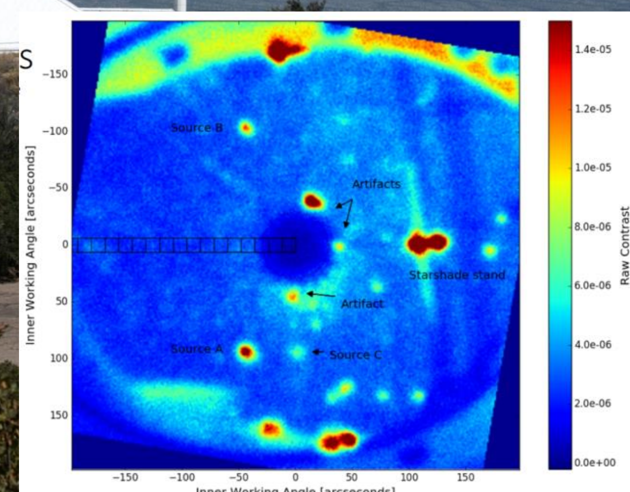
POC: David Webb (JPL)

Petal Launch Restraint and Unfurling System

- Developed with SBIR partners Tendeg and Roccor
- Simulated petal spines wrapped around a full-scale simulated perimeter truss and spacecraft
- Petal launch restraints embedded in petals

POC: David Webb (JPL)

Optical Testing at the McMath Solar Telescope

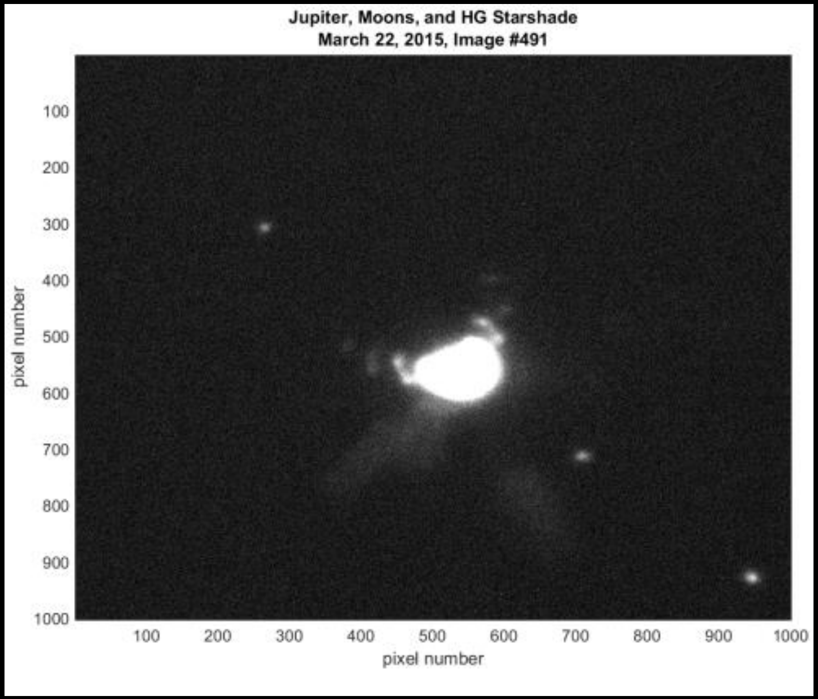


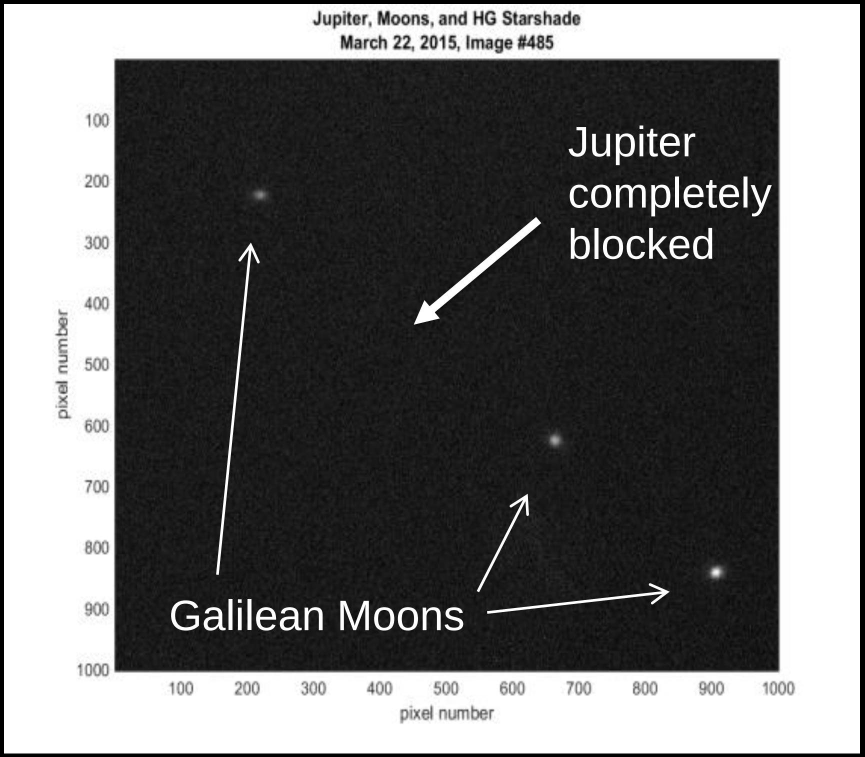
POC: Steve Warwick (NGAS), Web Cash/Anthony Harness (UC-Boulder)

Credit: Northrop Grumman Aerospace Systems

Approved for public release; NGAS Case 15-1679 dated 8/26/15.

Optical Demonstrations at McMath-Pierce Solar Telescope

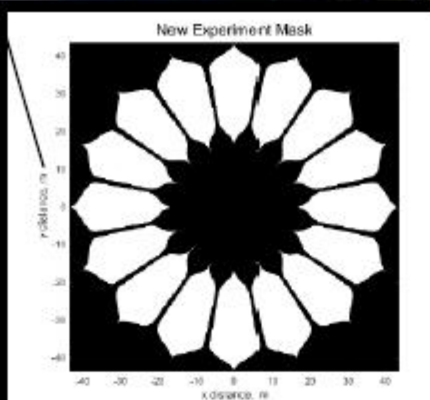


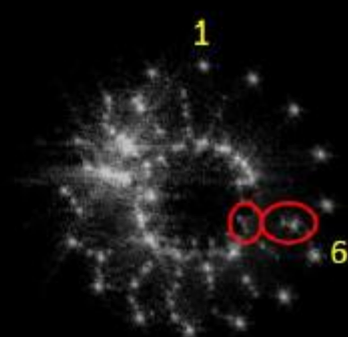


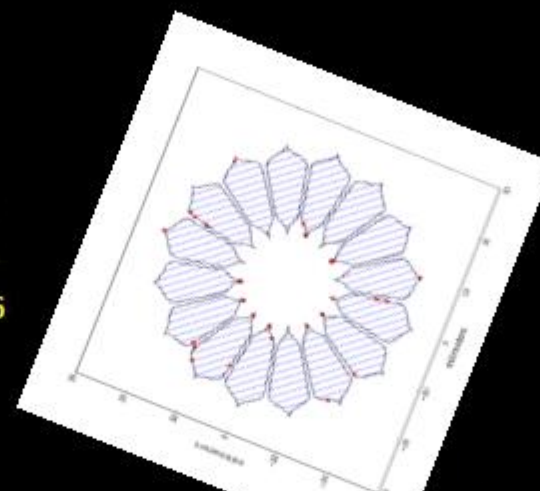
POC: Steve Warwick (Northrop Grumman Aerospace Systems)

Optical Demonstrations at Princeton

- Goal is to observe 1e-9 suppression – consistent with flight requirements and about 3 orders of magnitude deeper than previous tests.



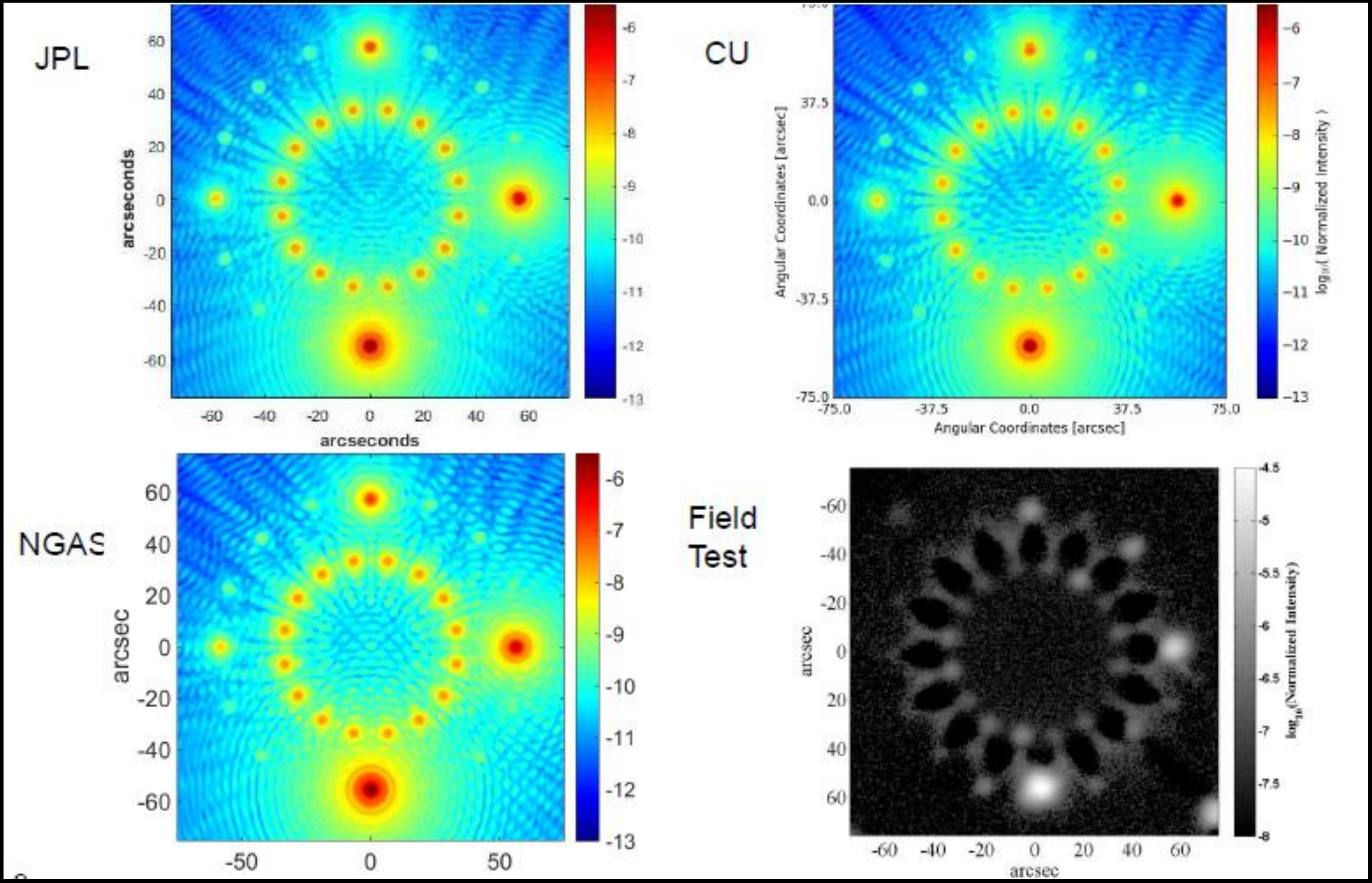




POC: Jeremy Kasdin (Princeton)

Optical Modeling Convergence

Intentionally flawed starshade

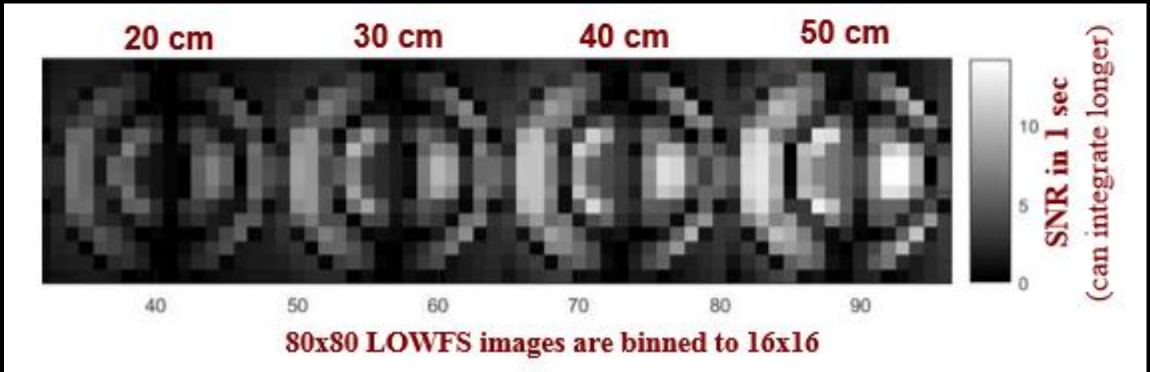


POC: Jeremy Kasdin (Princeton), Web Cash/Anthony Harness (UC-Boulder), Steve Warwick (NGAS), Stuart Shaklan (JPL)

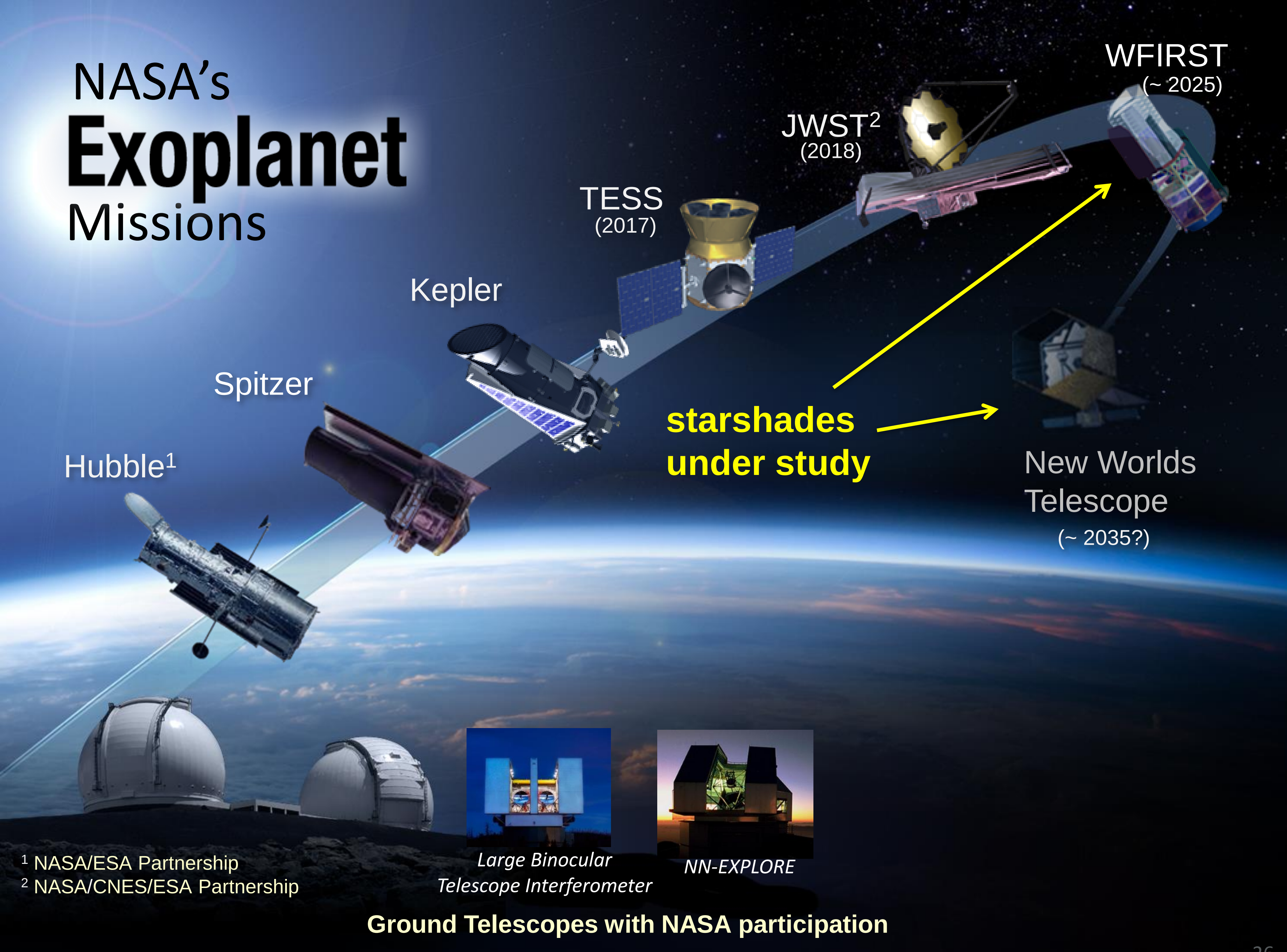
Formation Sensing

- Novel approach using WFIRST as a reference mission:
  - Coarse acquisition: Starshade Acquisition Camera
    - *Alternative: existing WFIRST Wide-Field Camera*
  - Intermediate acquisition: existing WFIRST Coronagraph Imager
  - Final acquisition: existing WFIRST Coronagraph Low-Order Wavefront Sensor

- Using pupil plane wavefront sensor reduces contrast requirement between starshade laser beacon and leaked out-of-band stellar diffraction
  - Starshade drift to the right clearly shows in the pupil plane



POC: Doug Lisman (JPL)



NASA's
Exoplanet
Missions
WFIRST
(~ 2025)
JWST[2]
(2018)
TESS
(2017)
Kepler
Spitzer
Hubble[1]
starshades
under study
New Worlds
Telescope
(~ 2035?)
Large Binocular
Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership
Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

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

Additional Slides

Towards the Detection of Exo-Earths