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

March 2016:
Starshade Technology Development Activity Chartered

TDEM Program

(PI-led activities)

→

Technology Development Activity

(projectized)

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
  - > 50% work outside

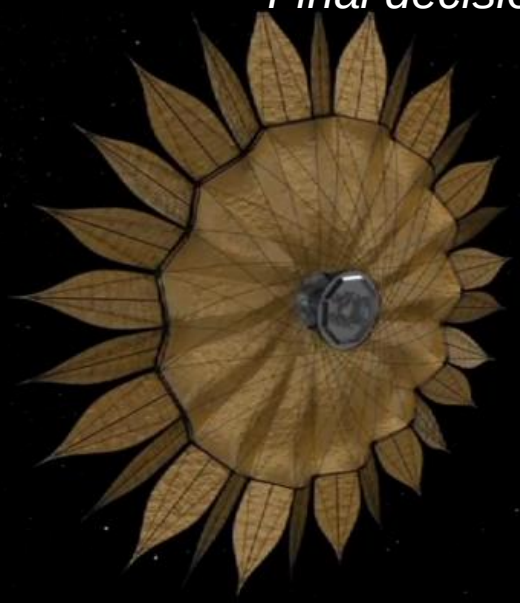
Key Goals and Deliverables of the Starshade Technology Activity

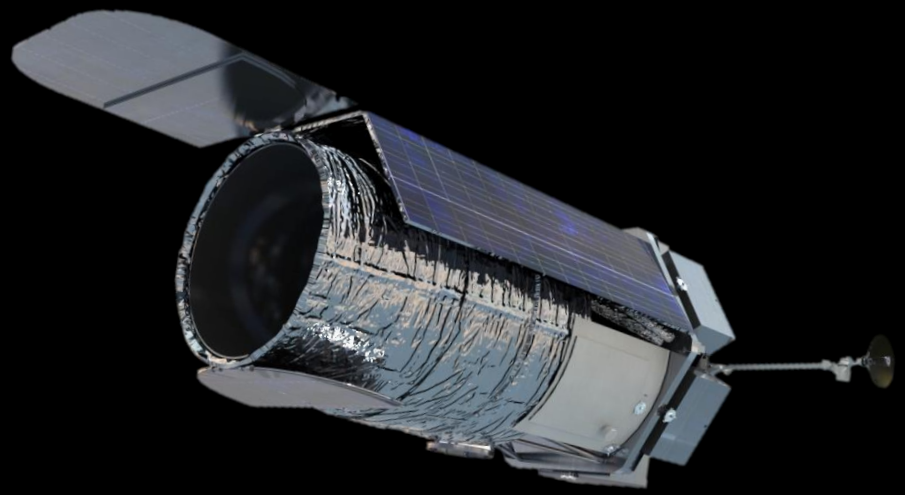
- Advance the technology readiness of the starshade to TRL-5
  - In Year 1:
    - TRL 5 Technology Development Plan
    - TRL 5 success criteria (vetted by an external review board)
    - key milestones with verification approaches
    - high-confidence cost and schedule estimates
    - key trade studies
    - 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*





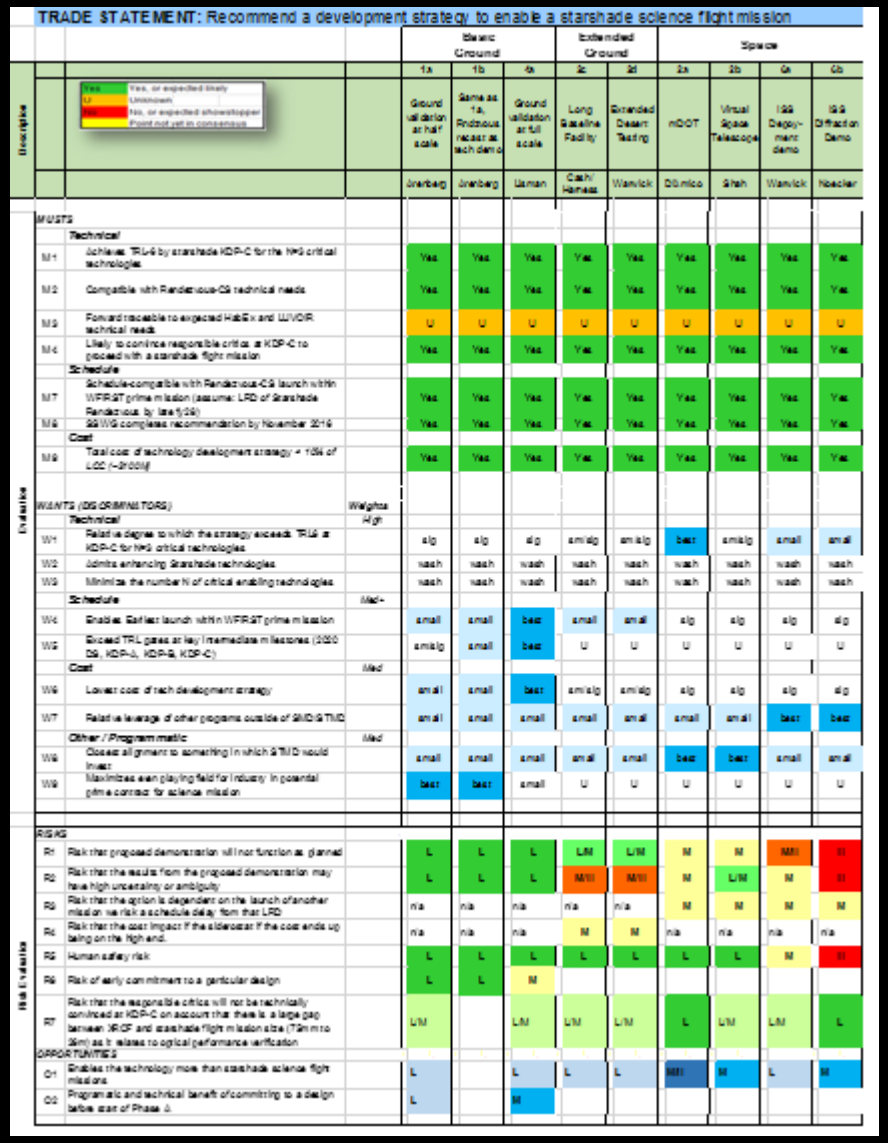
POC: John Ziemer, Doug Lisman (JPL)

November 2016:
Starshade Readiness Working Group Concludes

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

POC: Charley Noecker, Nick Siegler(JPL)

Starshade Readiness Working Group



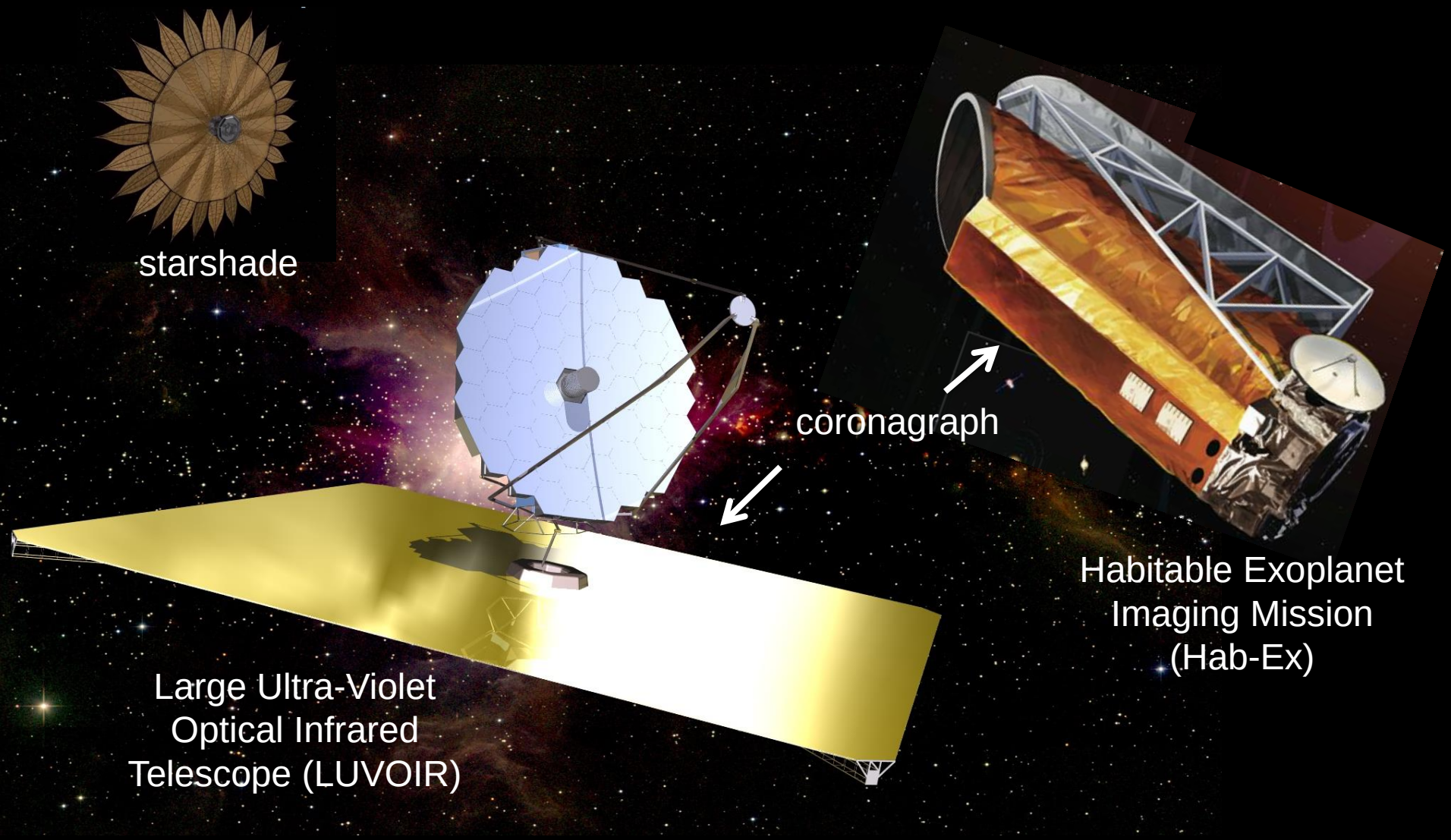
TRADE STATEMENT: Recommend a development strategy to enable a starshade science flight mission

				Bewc Ground			Extended Ground		Space			
				1a	1b	4a	2c	2d	2a	2b	6a	6b
				Ground validation at half scale	Same as 1a, Rndzvous recast as tech demo	Ground validation at full scale	Long Baseline Facility	Extended Desert Testing	mDOT	Virtual Space Telescope	ISS Deployment demo	ISS Diffraction Demo
				Jvenberg	Jvenberg	Usman	Cash/ Harness	Warwick	D'Amico	Shah	Warwick	Noecker
Descriptive												
Evaluative	MUSTS											
		Technical										
	M1	Achieves TRL-6 by starshade KDP-C for the N=3 critical technologies		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	M2	Compatible with Rendezvous-CS technical needs		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	M3	Forward traceable to expected HabEx and LUVOIR technical needs		U	U	U	U	U	U	U	U	U
	M4	Likely to convince responsible critics at KDP-C to proceed with a starshade flight mission		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
		Schedule										
	M7	Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission (assume: LFD of Starshade Rendezvous by late fy29)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	M8	SSWG completes recommendation by November 2019		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
		Cost										
	M9	Total cost of technology development strategy < 10% of LCC (~$100M)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	WANTS (DISCRIMINATORS)		Weights									
		Technical	High									
	W1	Relative degree to which the strategy exceeds TRL-6 at KDP-C for N=3 critical technologies		sig	sig	sig	smisig	smisig	best	smisig	small	small
	W2	Admits enhancing Starshade technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash
	W3	Minimize the number N of critical enabling technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash
		Schedule	Med+									
	W4	Enables Earliest launch within WFIRST prime mission		small	small	best	small	small	sig	sig	sig	sig
	W5	Exceed TRL gates at key intermediate milestones (2020 DS, KDP-A, KDP-B, KDP-C)		smisig	small	best	U	U	U	U	U	U
		Cost	Med									
	W6	Lowest cost of tech development strategy		small	small	best	smisig	smisig	sig	sig	sig	sig
	W7	Relative leverage of other programs outside of SMD/STMD		small	small	small	small	small	small	small	best	best
		Other / Programmatic	Med									
	W8	Closest alignment to something in which STMD would invest		small	small	small	small	small	best	best	small	small
	W9	Maximizes even playing field for industry in potential prime contract for science mission		best	best	small	U	U	U	U	U	U
Risk Evaluative	RISKS											
	R1	Risk that proposed demonstration will not function as planned		L	L	L	L/M	L/M	M	M	M/H	H
	R2	Risk that the results from the proposed demonstration may have high uncertainty or ambiguity		L	L	L	M/H	M/H	M	L/M	M	H
	R3	Risk that the option is dependent on the launch of another mission we risk a schedule delay from that LFD		n/a	n/a	n/a	n/a	n/a	M	M	M	M
	R4	Risk that the cost impact if the siderostat if the cost ends up being on the high end.		n/a	n/a	n/a	M	M	n/a	n/a	n/a	n/a
	R5	Human safety risk		L	L	L	L	L	L	L	M	H
	R6	Risk of early commitment to a particular design		L	L	M						
	R7	Risk that the responsible critics will not be technically convinced at KDP-C on account that there is a large gap between XRCF and starshade flight mission size (75m to 26m) as it relates to optical performance verification		L/M		L/M	L/M	L/M	L	L/M	L/M	L
	OPPORTUNITIES											
	O1	Enables the technology more than starshade science flight missions		L		L	L	L	M/H	M	L	M
	O2	Programatic and technical benefit of committing to a design before start of Phase A		L		M						

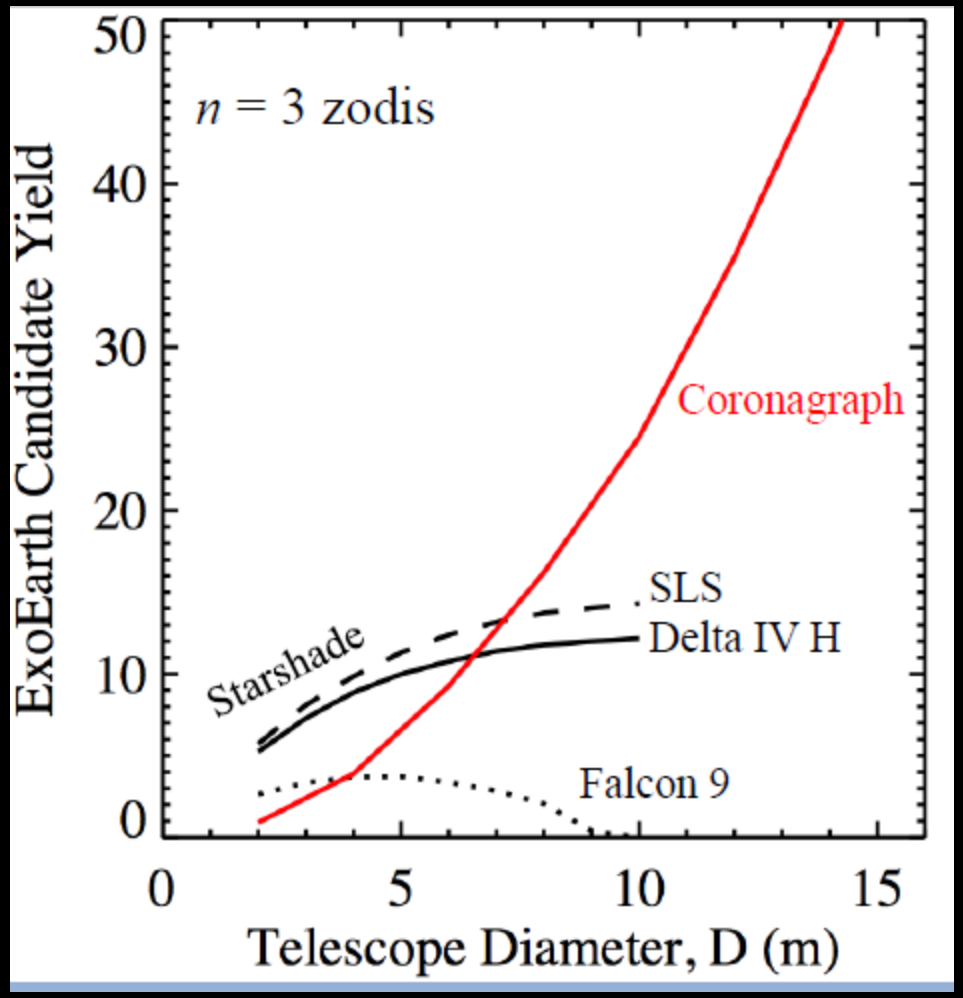
https://exoplanets.nasa.gov/exep/studies/sswg/

- 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 the technology development for formation flying sensing and control along with optical performance but at additional costs and risk

Ongoing:
Next Generation Exo-Planet Mission Studies



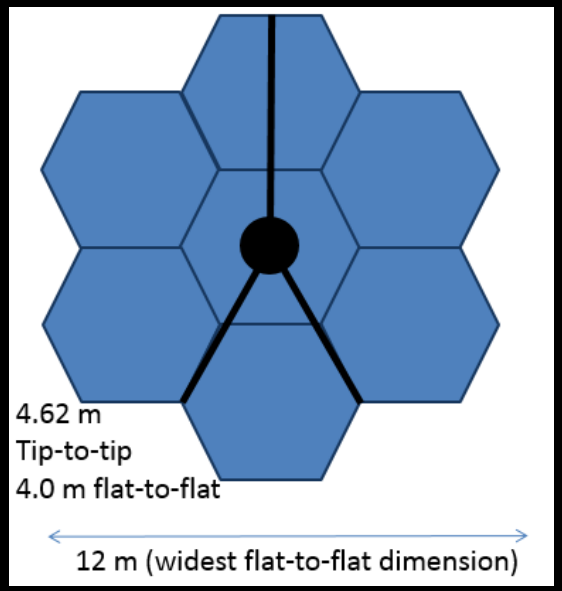
Next Generation Exo-Planet Mission Studies

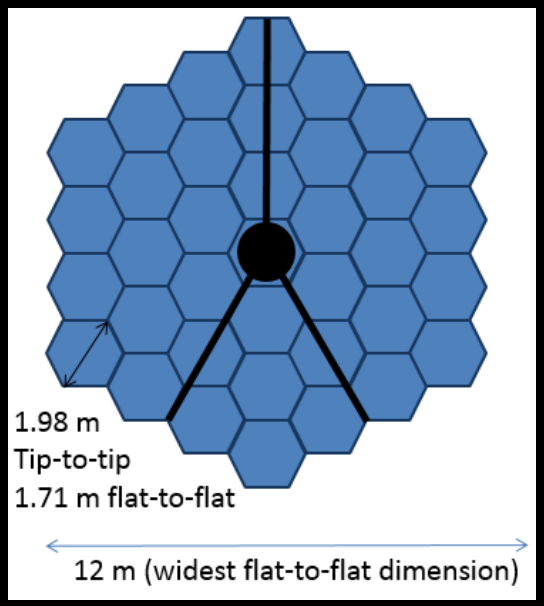


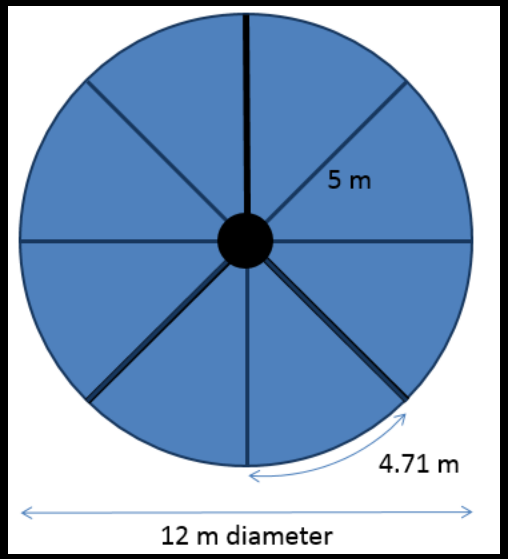
Chris Stark (STScI) et al. 2016

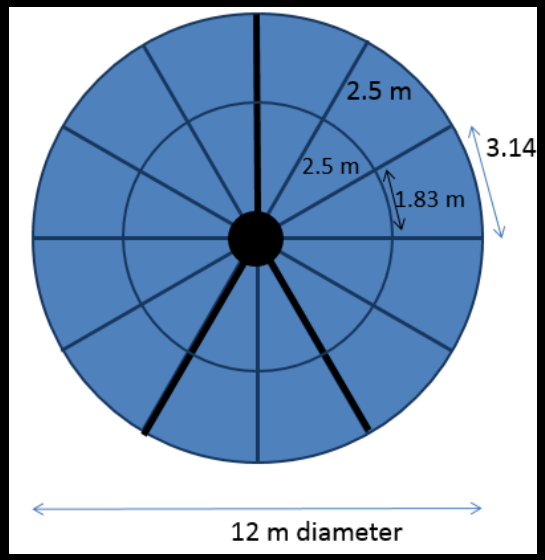
Next Generation Exo-Planet Mission Studies

ExEP Segmented Coronagraph Design and Analysis Study







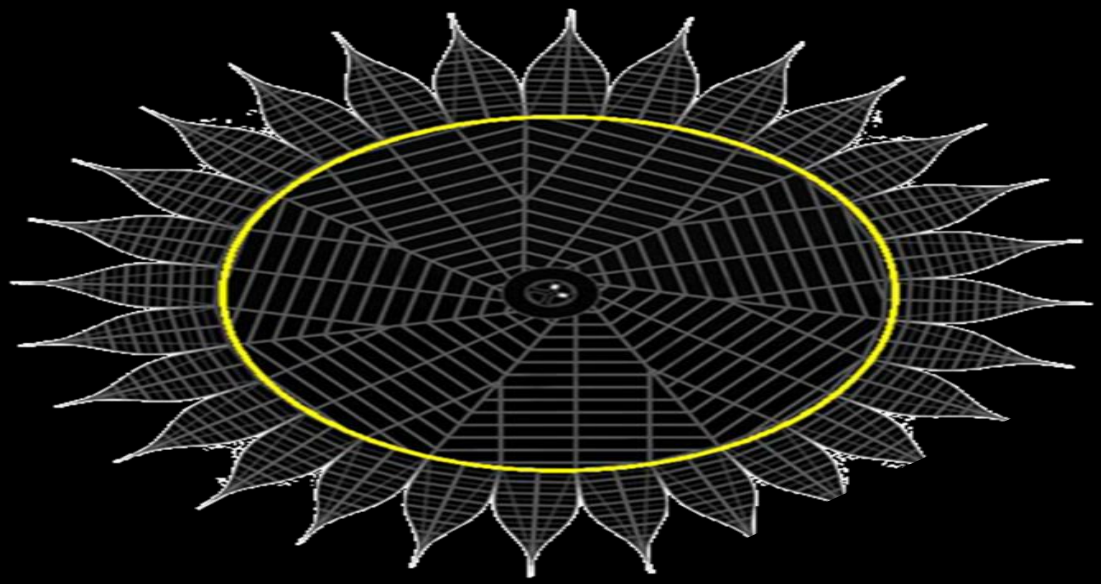


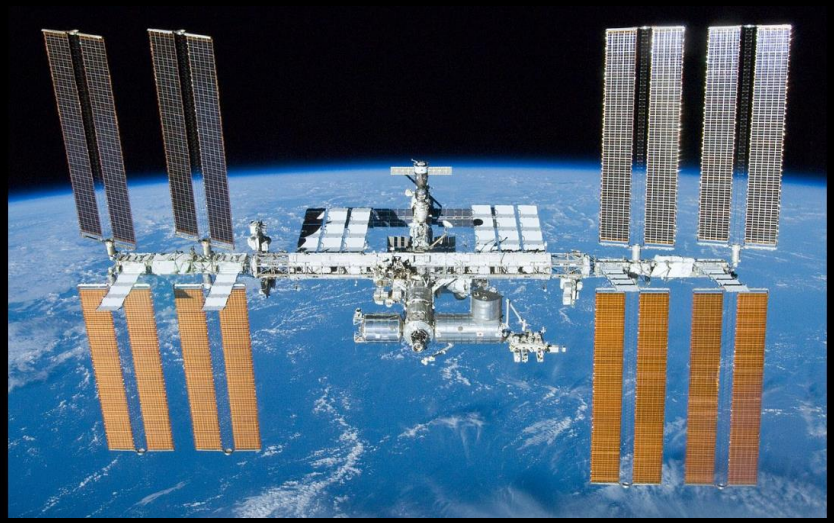
In search of coronagraph designs capable of achieving 10^{-10} contrast with large segmented telescope primary mirrors

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

POC: Stuart Shaklan (JPL)

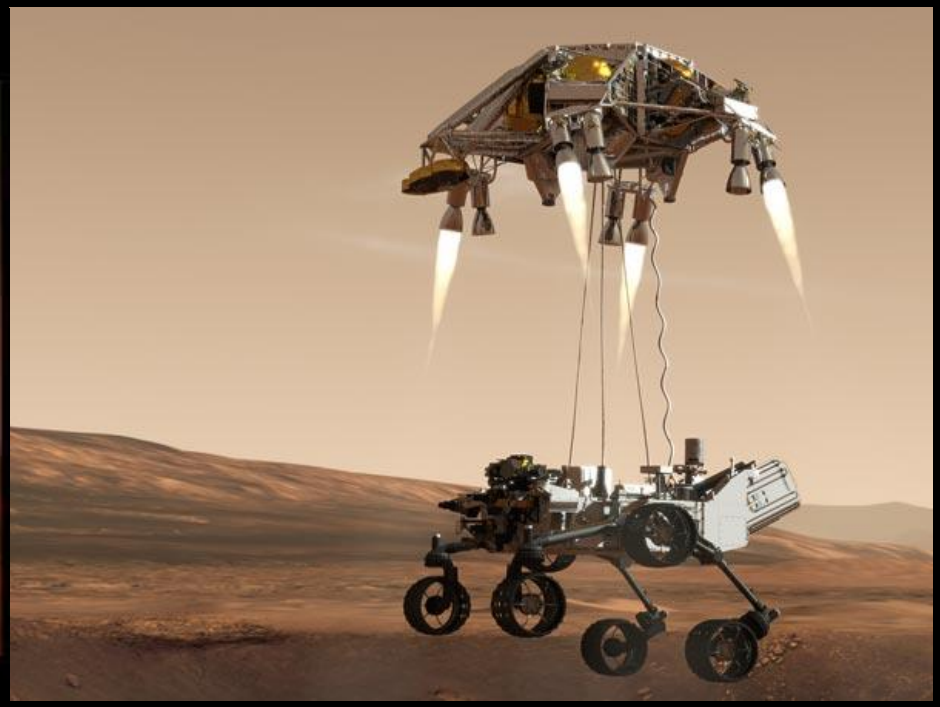
100m-class Starshades?





73 m

1st generation
(Air Bags)

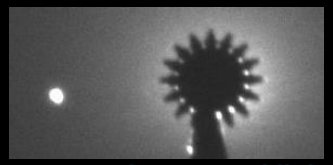


2nd generation
(Sky Crane)

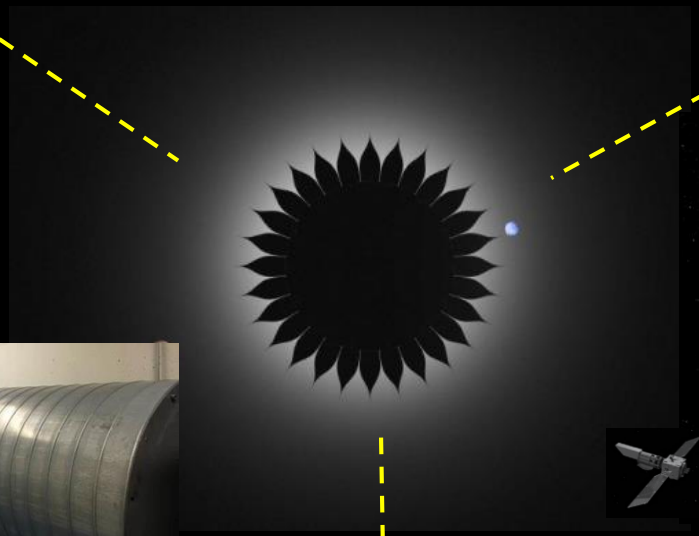
Starshade Technology Needs

Three Key Technology Areas for Starshades

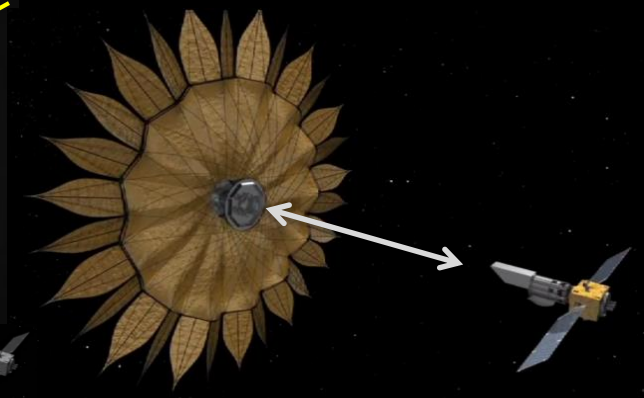
(1) Starlight Suppression



Suppressing scatted light off petal edges from off-axis Sunlight



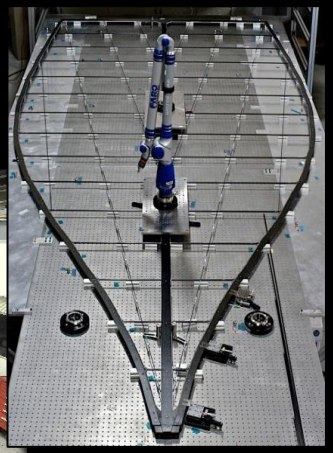
(3) Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts

Suppressing diffracted light from on-axis starlight

(2) Deployment Accuracy and Shape Stability



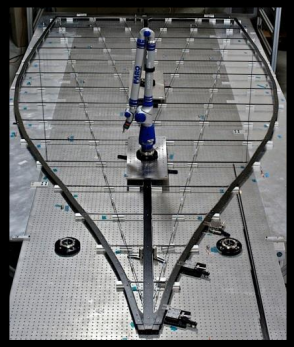
Fabricating the petals to high accuracy

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

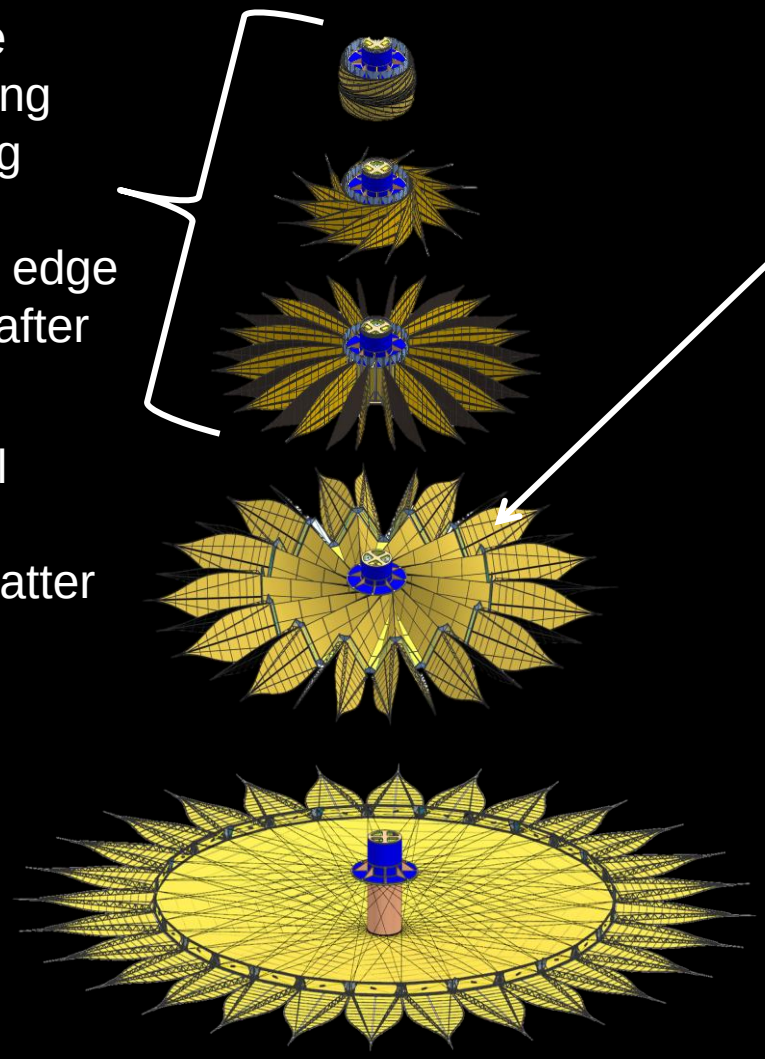
A Possible TRL-5 End State for a Starshade

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

(1) full-scale 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

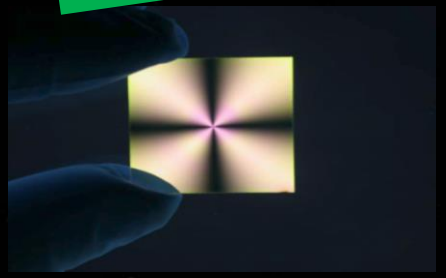
(7) Error budget and draft requirements for a possible mission concept

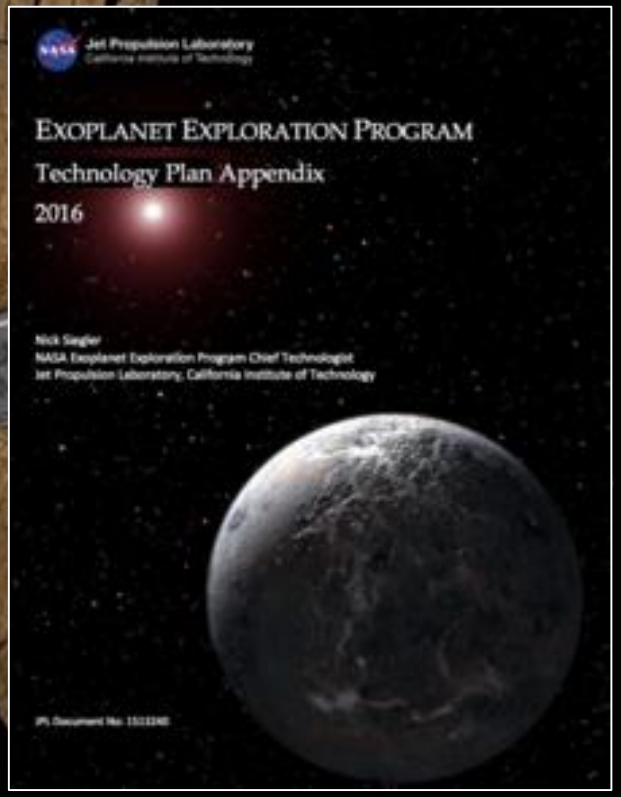
(8) Dynamic and thermal stability modeling

Path to TRL-6

2017 ExEP Technology Plan

To be 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 and 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.

Coronagraph/Telescope Technology Gap List

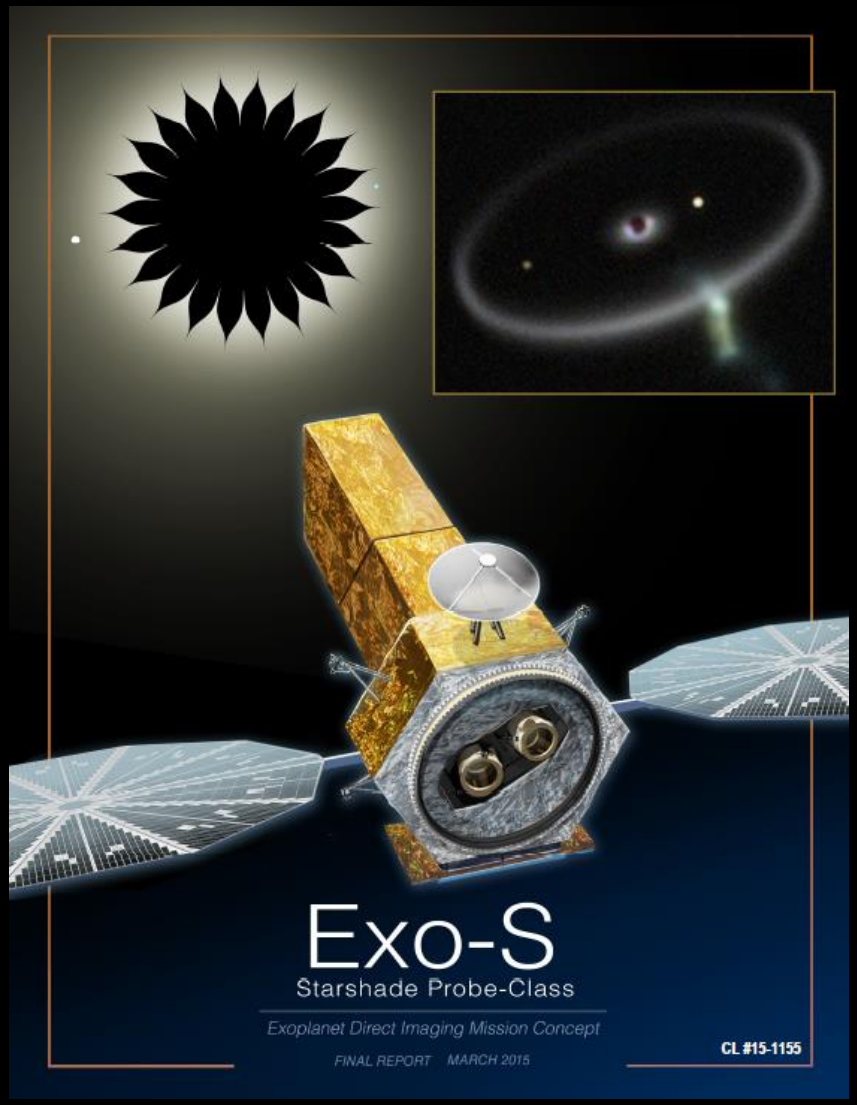
Table A.3 Coronagraph Technology Gap List.

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 $\leq 1\times10^{-10}$ 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^{-1}'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.

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

Exo-S Study (2015)



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

Starshade Technology Progress in 2016

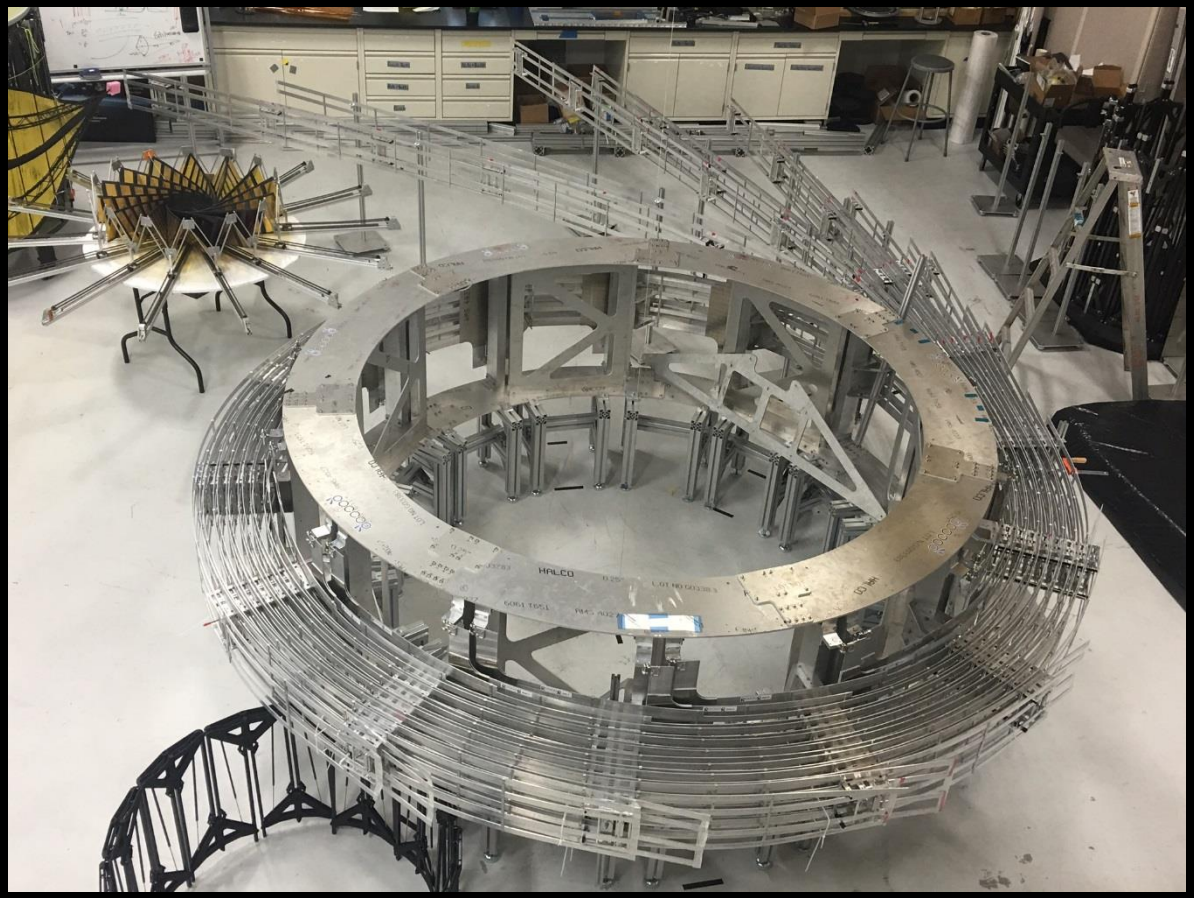
5 m Origami Optical Shield Deployment Trial at JPL

POC: David Webb (JPL)

5 m Optical Shield Prototype

POC: David Webb (JPL)

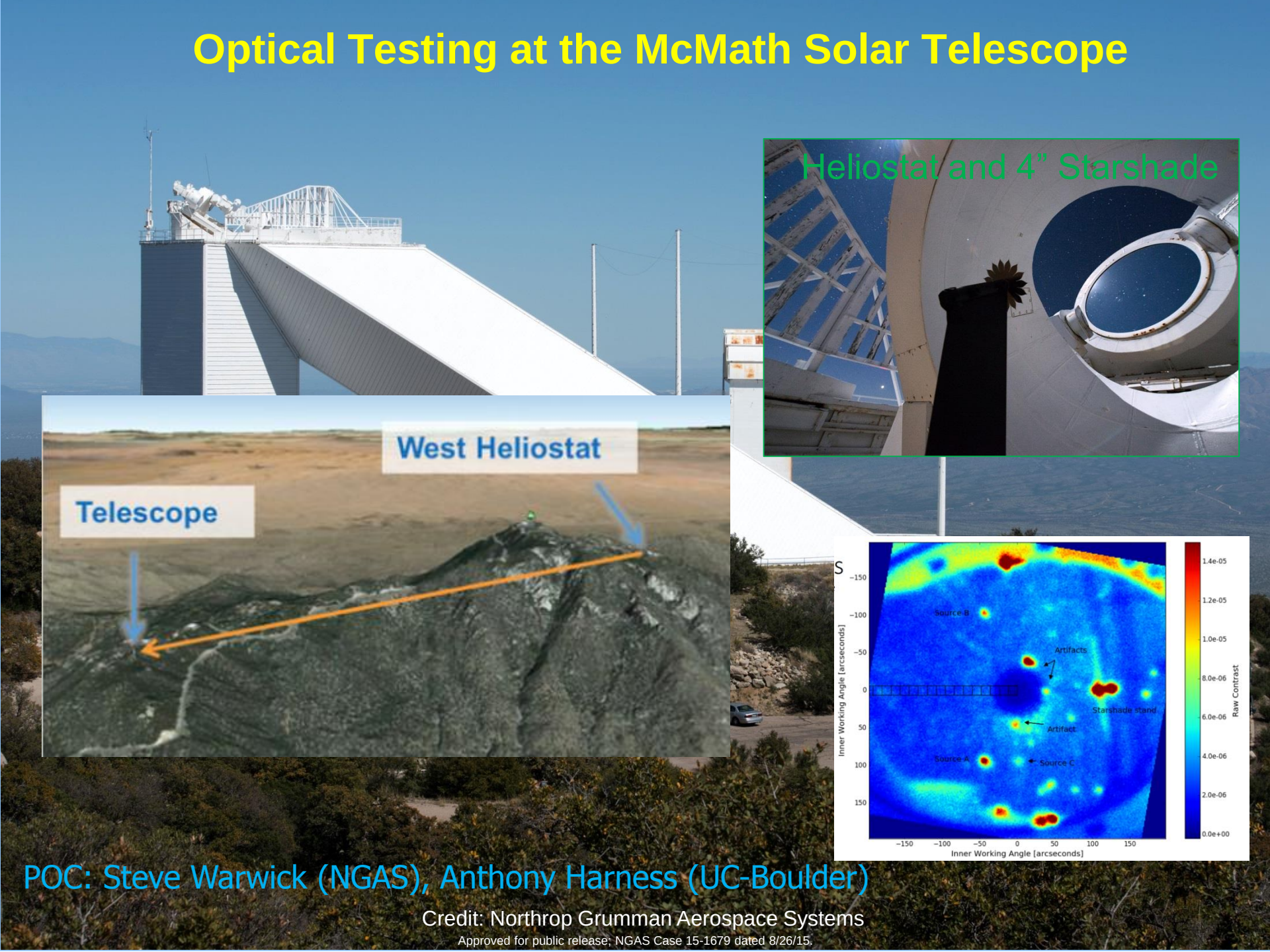
Petal Launch Restraint and Unfurling System



- 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

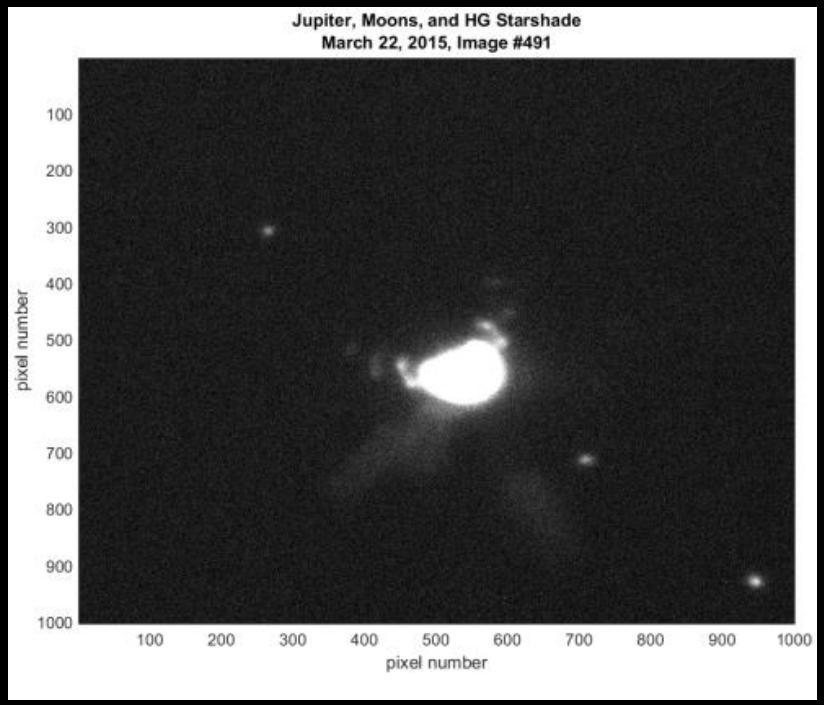


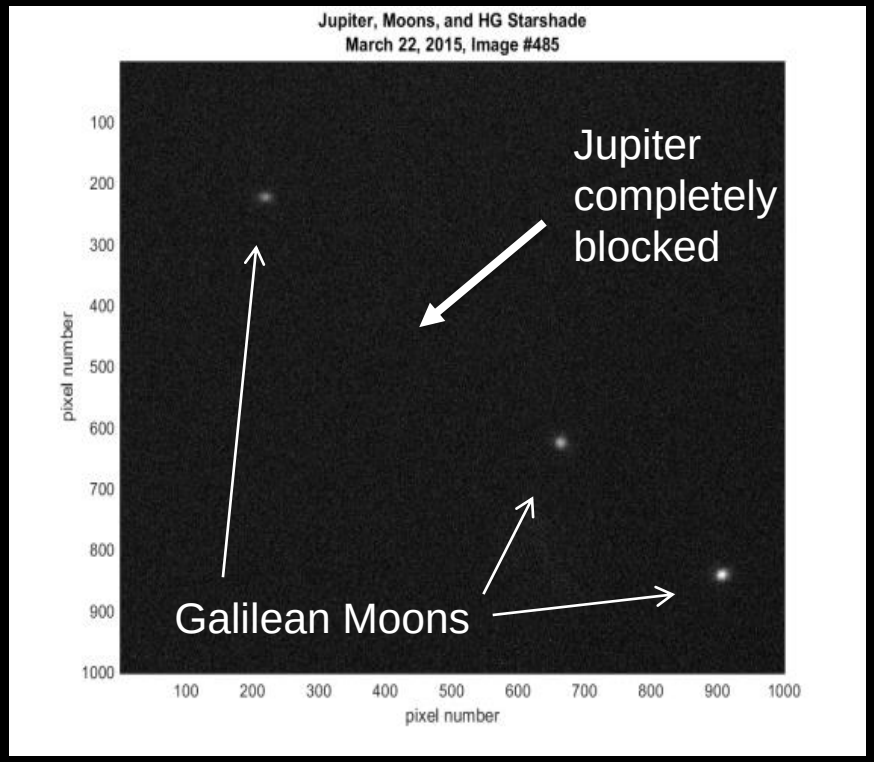
POC: Steve Warwick (NGAS), Anthony Harness (UC-Boulder)

Credit: Northrop Grumman Aerospace Systems

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

Optical Demonstrations at McMath-Pierce Solar Telescope

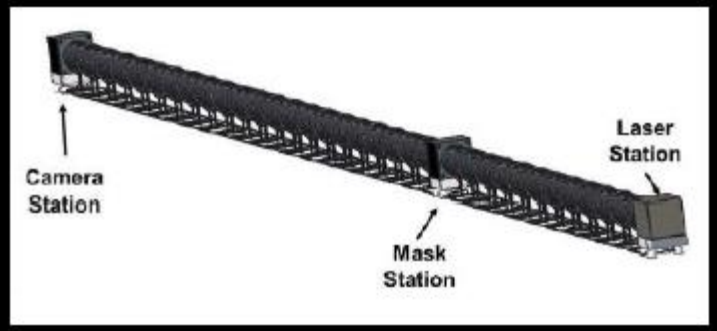


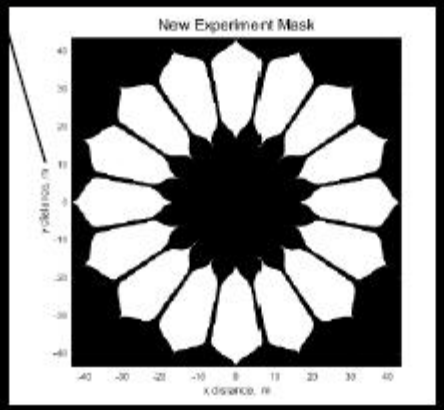


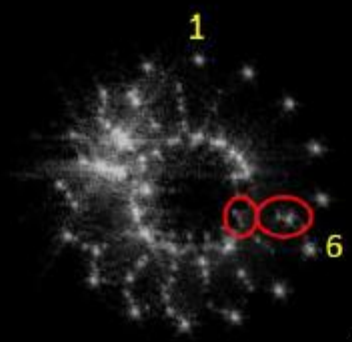
POC: Steve Warwick (Northrop Grumman Aerospace Systems)

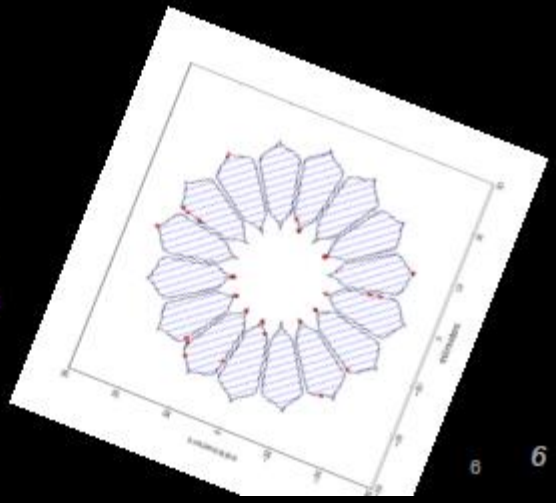
Optical Demonstrations at Princeton

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





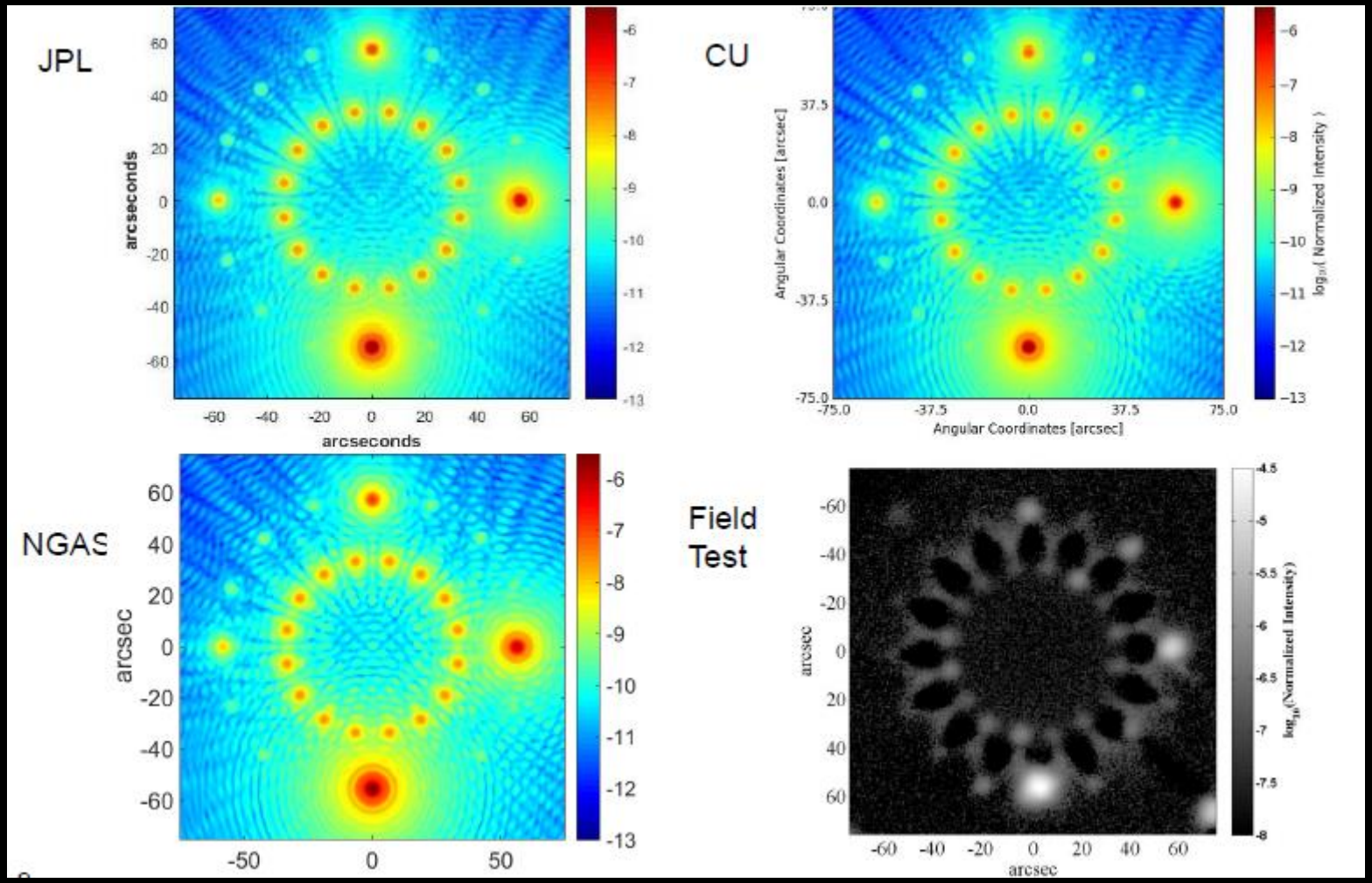




POC: Jeremy Kasdin (Princeton)

Optical Modeling Convergence

Intentionally flawed starshade

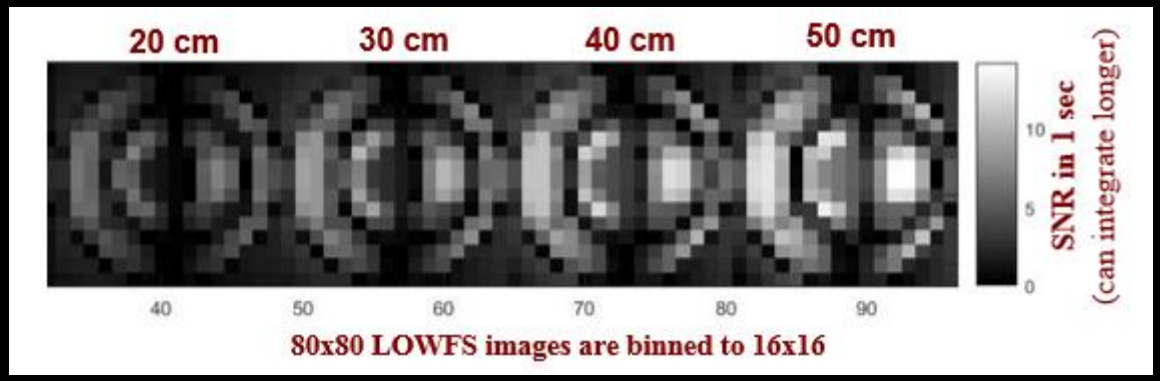


POC: Jeremy Kasdin (Princeton), Anthony Harness (UC-Boulder), Steve Warwick (NGAS), Stuart Shaklan (JPL)

Formation Sensing

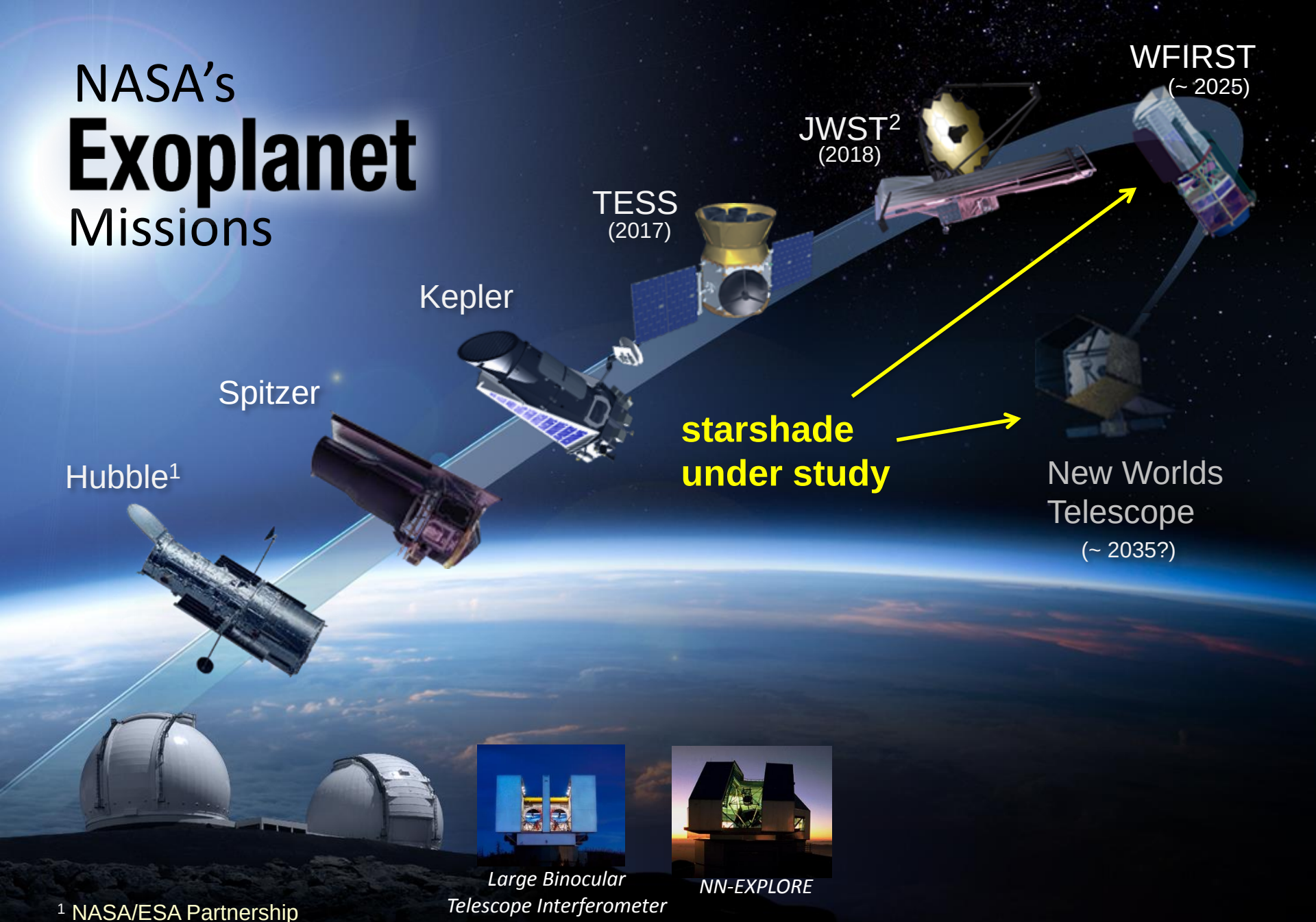
- Novel approach using WFIRST as a reference mission:
  - Coarse acquisition: existing WFIRST Wide-Field Camera
  - Intermediate acquisition: existing WFIRST Coronagraph Imager
  - Final acquisition: existing WFIRST Coronagraph Low-Order Wavefront Sensor

- Using pupil plane wavefront senor 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



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

Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

Additional Slides

Possible TRL-5 End State

Technology Area	Key Performance Tolerances (3σ)	Proposed End-State Fidelity (TRL-5+)			Tested in Relevant Environment; Designed to Meet Life Rqmt	Performance Verification	Model Validation
		Fit	Form	Function			
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 100 µm	High fidelity, full-scale	High-fidelity prototype	Required performance demonstrated	Deploy and thermal cycles	Measure shape after deployment and thermal cycles	CTE, CME, creep
					Temperature and humidity	Measure shape with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Predict on-orbit petal shape with all errors	Shape vs. temperature
	Petal Deployment Accuracy						
	In-plane envelope: ± 1 mm	High fidelity, half-scale inner disk; scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	0-gravity and vacuum	Measure position after deployment cycles in air with negligible air drag and imperfect gravity comp.	CTE, CME, creep
					Temperature and humidity	Measure position with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Analyze on-orbit petal shape with all errors	Shape vs. temperature
Formation Sensing and Control	**Bearing Angle Sensing and Control**						
	Sensing: ± 1 mas Control (modeling): ± 1 m	Medium fidelity, using small-scale starshade; scaling issues	Medium-fidelity prototype	Basic functionality demonstrated	Large separation distance	Measure angular offsets with brassboard guide camera (coronagraph instrument) that simulates PSFs and fluxes from beacon and star	PSFs bearing angle vs. signal
Contrast	**Scattered Sunlight**						
	Edge radius x reflectivity: ≤ 10 µm-%	High fidelity, full-scale petal with full-scale optical edges	High-fidelity prototype	Required performance demonstrated with critical interfaces	Same as for petal shape	Measure petal level scatter after environment tests at discrete angles	Scatter vs. sun angle Scatter vs. dust
					Sun angle	Measure coupon level scatter after environment tests at all sun angles	
					Dust in launch fairing	Analyze effect for on-orbit solar glint	
	Starlight Suppression						
	Test at a flight-like Fresnel: Contrast (test) < 10^{-9} (traceable to 10^{-10} system performance with validated model)	Medium fidelity, small-scale starshade; scaling issues understood	Medium-fidelity prototype	Basic functionality demonstrated	Space	Measure image plane contrast between 500-850 nm	Optical performance, sensitivity to perturbations

(to be concurred by a TAC at the end of Starshade Technology Project Formulation)