Jet Propulsion Laboratory
California Institute of Technology

Starshade Mission Concepts, Technology, and Starshade Readiness Working Group

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Miniaturized Distributed Occulter Telescope (mDOT) Workshop,

Stanford University

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NASA Exoplanet Exploration Program

A Program within the NASA Astrophysics Division

Purpose described in
2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

The Search for Life in our Galaxy

ExEP serves the science community and NASA APD by
Implementing NASA's space science vision for exoplanets

http://exep.jpl.nasa.gov

NASA Exoplanet Exploration Program

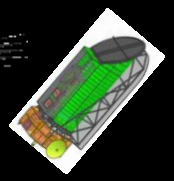
Space Missions and Mission Studies

Kepler, K2

WFIRST-AFTA

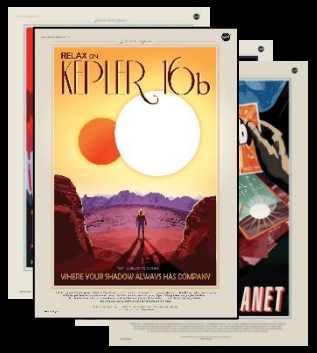
Decadal Studies Probe-Scale

Starshade



Coronagraph

Public Communications

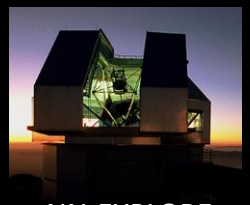


Supporting Research & Technology

Key Sustaining Research

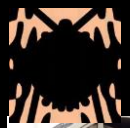
Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV



NN-EXPLORE

Technology Development



Coronagraph Masks

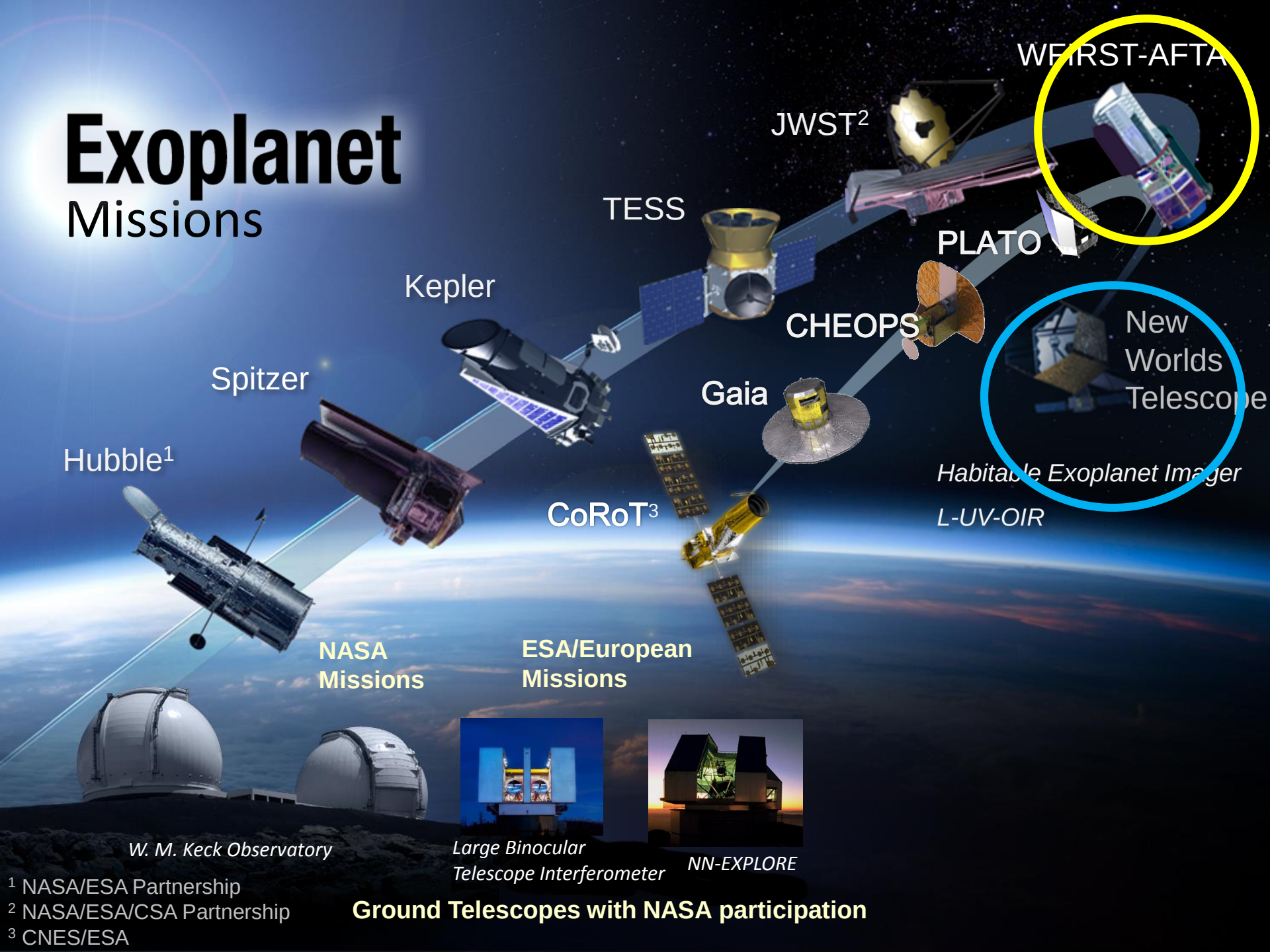
High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

Exoplanet Missions



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

Ground Telescopes with NASA participation

Mission Concepts that Employ a Starshade

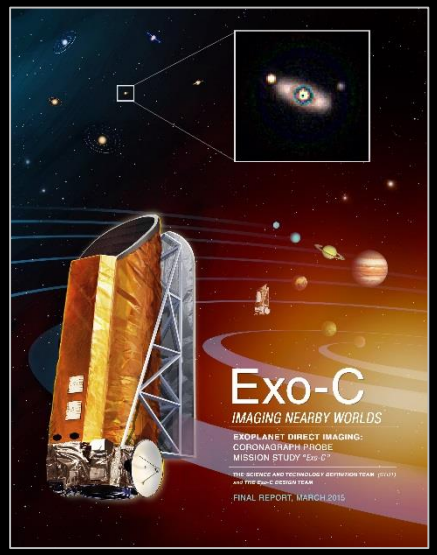
- Exoplanet Probe Studies (2013-15)
  - Exo-S Stand Alone (30m shade, 1.1m aperture)
  - Exo-S Rendezvous CS (34m shade, 2.4m aperture)
- Probe Extended Studies (2016)
  - Exo-S Rendezvous ES (use SEP for starshade)
  - Alternative architectures (Cash et al)
- Decadal Large Mission Studies (2016-19)
  - Habitable Exoplanet Imager
  - LUVOIR

Probe-Scale studies

High-Contrast Imaging

Purpose
- Alternatives for 2017 new start
- Motivate technology investments
- Candidates for next Decadal Survey

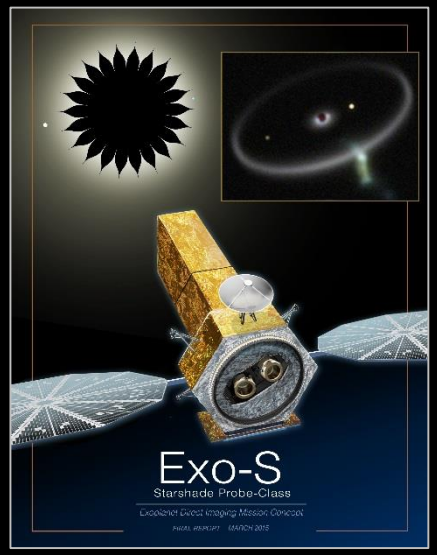
Ground rules:
- Compelling Science beyond ground capability at time of mission
- $1B LCC confirmed by Aerospace CATE
- Launch 2024
- TRL 5 by end of Phase A, TRL 6 by end of Phase B



Exo-C:

Internal Occulter (Coronagraph)

K. Stapelfeldt, STDT Chair, GSFC



Exo-S:

External Occulter (Starshade)

S. Seager, STDT Chair, MIT

Exo-S Mission Concepts

Dedicated (Co-Launched) Mission

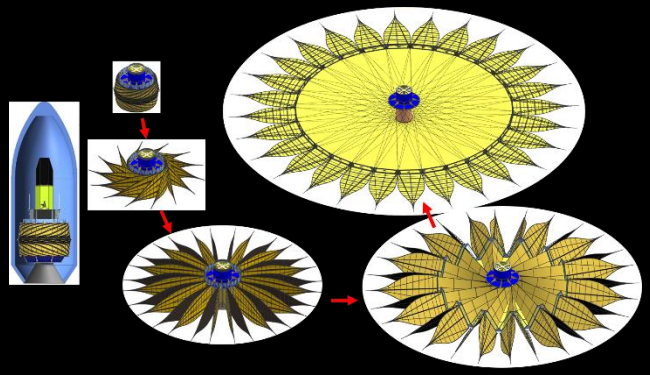
- Telescope: 1.1 m
- Retargeting: by the telescope s/c (SEP)
- $1.1B lifecycle cost

Rendezvous Mission

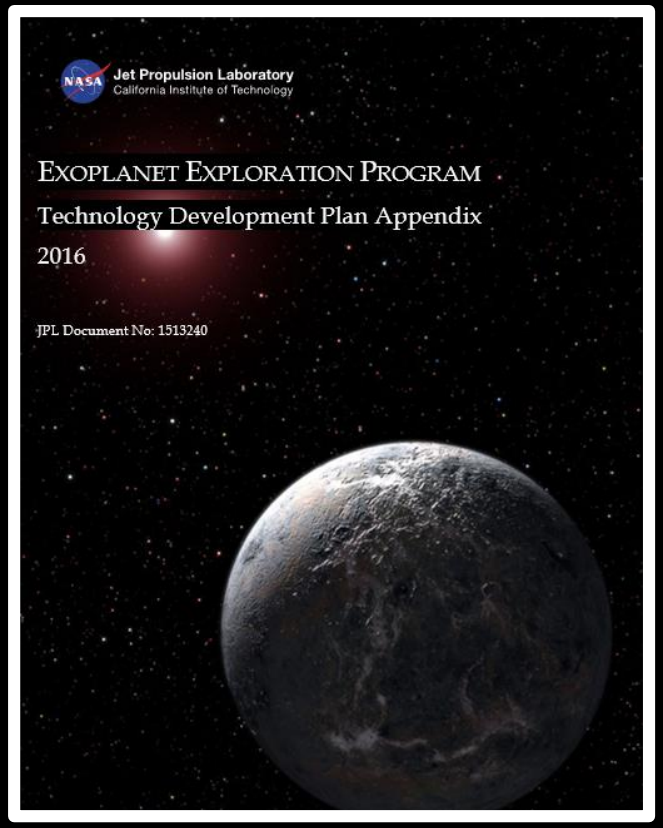
- Telescope: WFIRST/AFTA 2.4 m is adopted
- Orbit: Earth-Sun L2
- Retargeting: by the starshade spacecraft
- Minimal impact to telescope to be “starshade ready”
- $0.6B lifecycle cost

Common to both:

- Starshade design (30 m vs. 34 m diameter)
- Formation-flying over ~35,000 km separation
- 3 Year Mission
- Science:
  - Spectra or colors for ~30 planets.
  - Access to several Earths in HZ of their stars



NASA Exoplanet Exploration Program 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^{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.

Coronagraph Technology Gap List

Table A.4 Starshade Technology Gap List

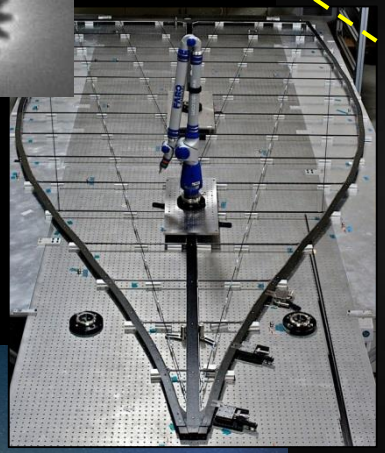
ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≤ 10%.
S-2	Contrast Performance Demonstration 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.

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

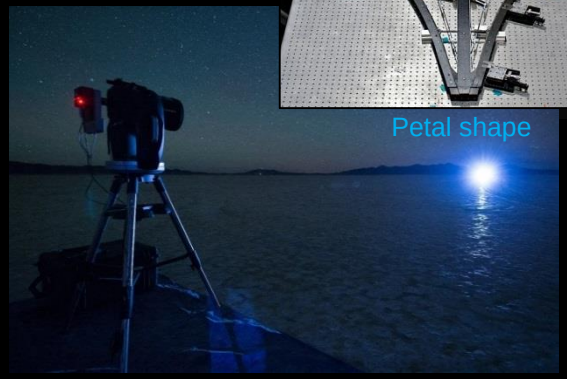
Starshade Technology Needs

Diffraction and Scattered Light Control

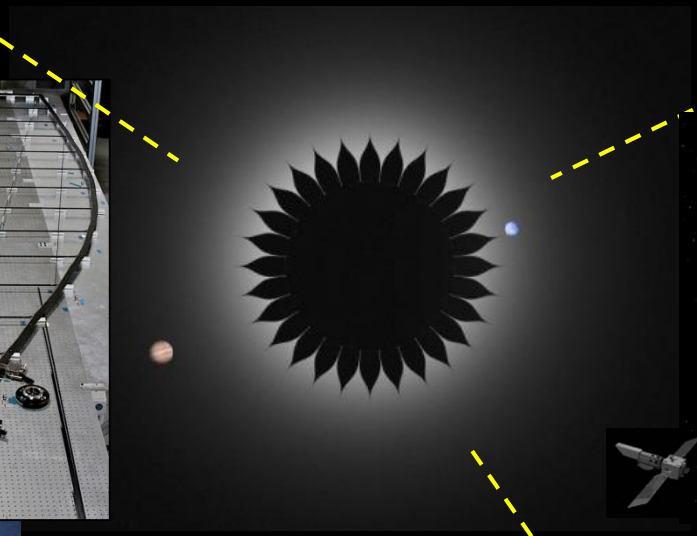
Solar glint



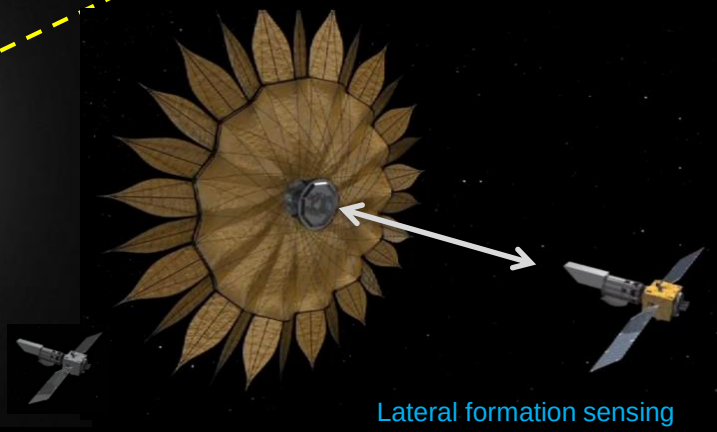
Petal shape



Optical demonstration and model validation



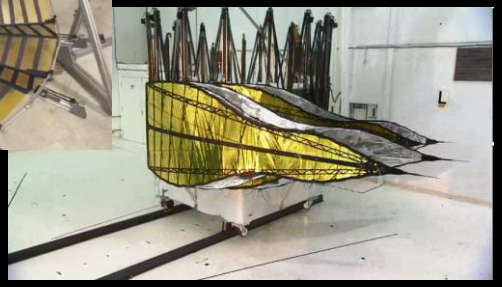
Lateral Formation Flying Sensing



Lateral formation sensing

Precision Deployable Structures

Inner disk deployment



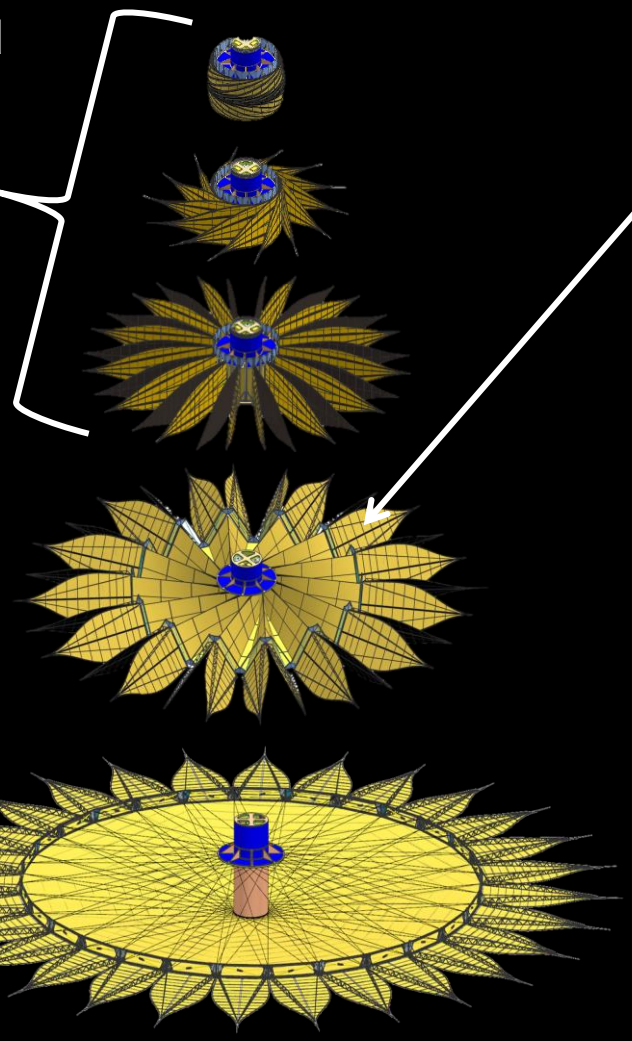
Petal deployment

Starshade Technology Gap List

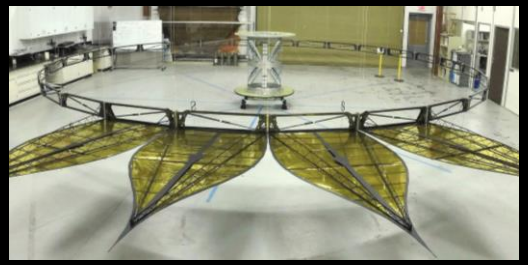
	ID	Title	Description	Current Capabilities	Needed Capabilities
Diffraction and Scattered Light Control	S-2	Optical Perf Demo and Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	$3x10^{-10}$ contrast at 632 nm, 5 cm mask, and ~500 Fresnel #; validated optical model $9x10^{-10}$ contrast at white light, 58 cm mask, and 210 Fresnel #	Experimentally validated models of contrast to < 10^{-10} in scaled flight-like geometry with Fresnel numbers ≤ 20 across a broadband optical bandpass.
	S-1	Solar Glint	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 maintain precision in-plane shape requirements after deployment trials and limit solar glint contributing < 10^{-10} contrast at petal edges.
Precision Structural Deployment	S-6	Petal Deployment	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.
Lateral Formation Flying Sensing	S-3	Lateral Formation Sensing	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.
Precision Structural Deployment	S-5	Inner Disk Deployment	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 to ≲ 1 mm with flight-like, minimum half-scale inner disk, with simulated petals, optical shield, and interfaces to launch restraint after exposure to relevant environments.
Diffraction and Scattered Light Control	S-4	Petal Shape	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 tolerance and maintains shape after multiple deployments from stowed configuration.

Technology Demonstrations to TRL 5

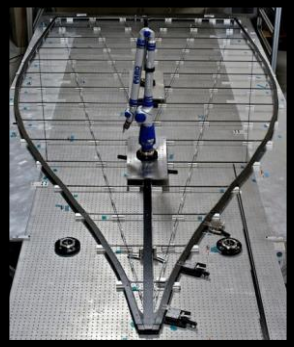
(2) Full-scale latching and unfurling mechanism verifying controlled petal deployment with no edge contact during and after launch



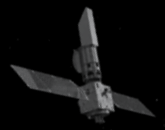
(3) Half-scale inner disk verifying deployment and petal positioning tolerances



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



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



Key validated models and analyses predicting:

(5) Optical performance with validated optical model

(6) Maximum micro-meteoroid hole area

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

The Starshade Technology Project

- Purpose: achieve TRL5 by 2019
- Directed funding and reprogramming of competed funds
- KDP-A (to enter Formulation) March 2016
- Managed by ExEP at JPL for APD, as a technology project
- Intent is broad institutional participation and funding

The Starshade Readiness Working Group (SSWG)

- Chartered by NASA APD: http://exep.jpl.nasa.gov/sswg/
- Require a risk reduction plan for technology validation of starshades to enable starshade flight science missions to be considered in 2020 Decadal Survey
- Will answer these questions and deliver recommendation to APD by July 2016:
  - How to go from TRL 5 to ~TRL6,7
  - Do we need a tech demo, and if so, what is it?
- Will adopt the Exo-S probe “Starshade Rendezvous” as representative motivation of technology requirements
- Will establish TRL and validation success criteria, generate options, choose the strongest recommendation (consensus) for APD
- Chairs: G. Blackwood (ExEP/JPL), S. Seager (MIT)

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California Institute of Technology

Acknolwedgements

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

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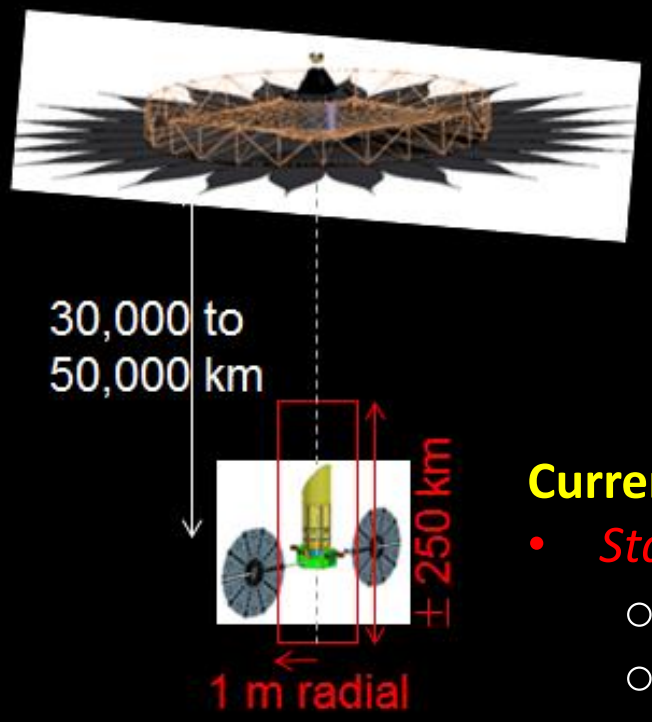
- Work was also carried out at NASA's:
  - Goddard Space Flight Center
  - Ames Research Center
- Work was carried out as well under contracts with the National Aeronautics and Space Administration and:
  - Princeton University
  - University of Arizona
  - Northrop Grumman Aerospace Systems
  - National Optical Astronomy Observatory (NOAO)
  - Massachusetts Institute of Technology
  - Penn State University

#5: Demonstrate Precision, Lateral Formation-Sensing over Simulated Long-Distances



Need:

- *Sense relative lateral offsets between telescope and starshade to enable ±1 m control at 50,000-km separations*
  - *≤ 30 cm sensing knowledge (≤ 1.25 mas angle offset)*
- *Demonstrate synchronized deadband control in two lateral axes with different disturbances over period of days*

Current Capabilities:

- *Starshade formation flying parameters are unique to NASA*
  - *HST Fine Guidance Sensors accurate to ~1 mas*
  - *ESA Proba 3 formation flying scheduled to measure 30 mas offset at ~150m*
  - *GRAIL and GRACE are ~200 km separations, no bearing control, just RF ranging*
- *Unsynchronized, short-term deadbanding for 30 min long rendezvous and docking*