Starshade Technology Development in NASA's Exoplanet Exploration Program

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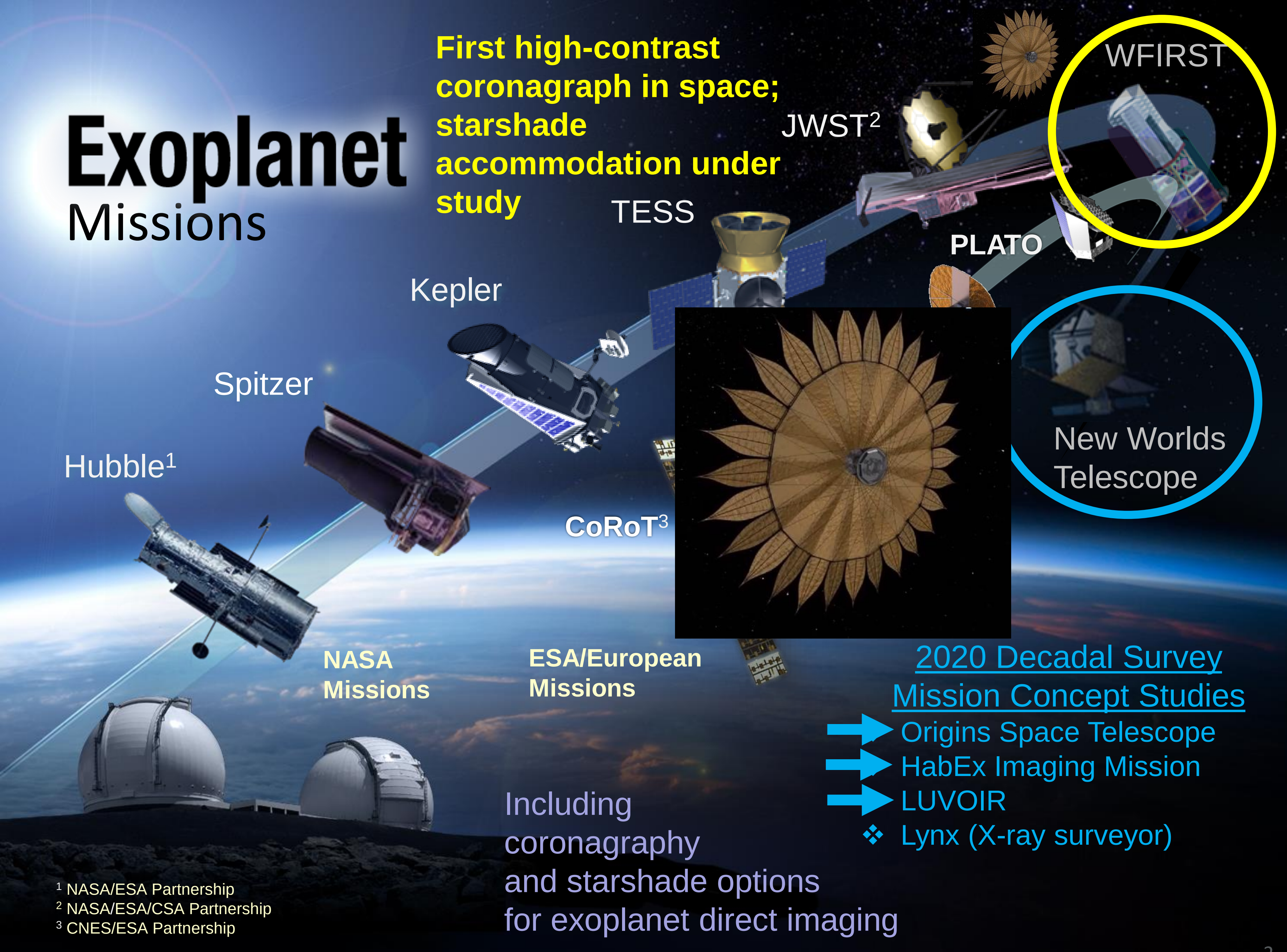

Exoplanet
Missions
First high-contrast coronagraph in space; starshade accommodation under study
JWST[2]
WFIRST
TESS
PLATO
Kepler
Spitzer
Hubble[1]
CoRoT[3]
New Worlds Telescope
NASA Missions
ESA/European Missions
2020 Decadal Survey Mission Concept Studies
Origins Space Telescope
HabEx Imaging Mission
LUVOIR
Lynx (X-ray surveyor)
Including coronagraphy and starshade options for exoplanet direct imaging
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA Partnership

ExEP Technology Plan Appendix and Technology Gap Lists

- ***Updated Annually via ExEP's Technology Selection and Prioritization Process***

Starshade Gaps

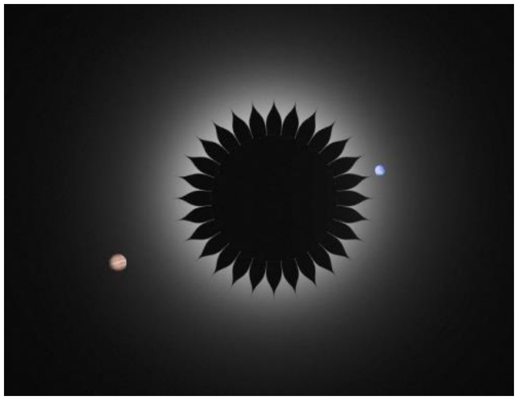
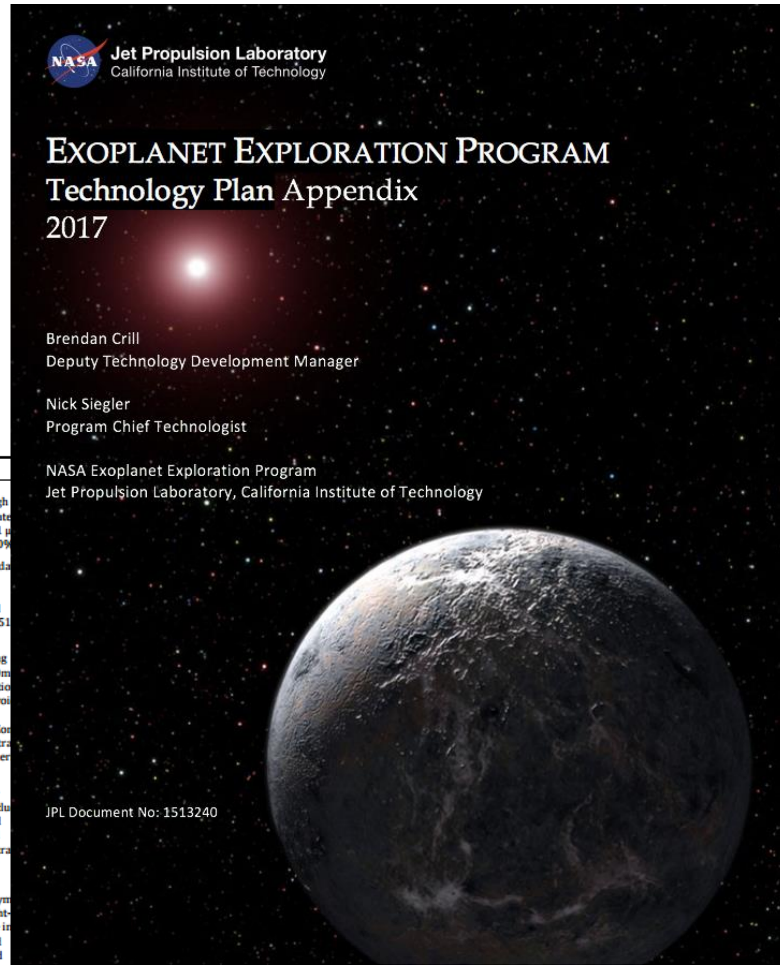
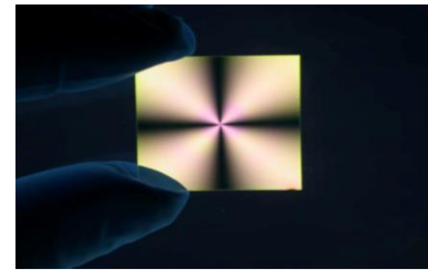


Table A.4 Starshade Technology Gap List

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 mate with edge radius ≤ 1 μ 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 valida models of starlight suppression to $\leq 3\times10^{-11}$ at Fresnel numbers ≤ 50 over 51 825 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 scaled flight separatio and estimated centroi positions ≤ 0.3% of optical resolution. Co algorithms demonstra with lateral control er ≤ 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, inclu blankets, edges, and deployment control interfaces. Demonstra 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 deploym tolerances with flight- minimum half-scale in disk, with simulated petals, blankets, and interfaces to launch restraint.



Coronagraph Gaps



Coronagraph Technology Gap List.

Title	Description	Current	Required
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 $\leq 3\lambda$/D and ≥ 10% bandwidth on obscured or segmented pupils.
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 $10^{-3}\lambda$ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to $10^{-4}\lambda$ (~10's of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ in a simulated dynamic testing environment.
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.
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.
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).
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.

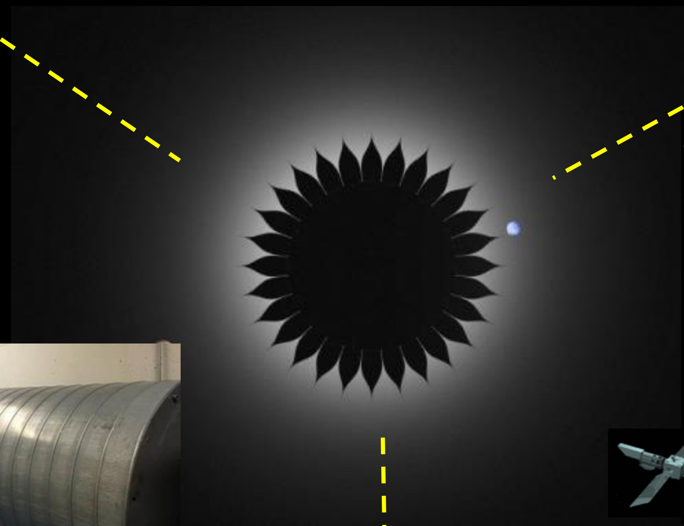
Most recent Appendix revision, January 2017

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

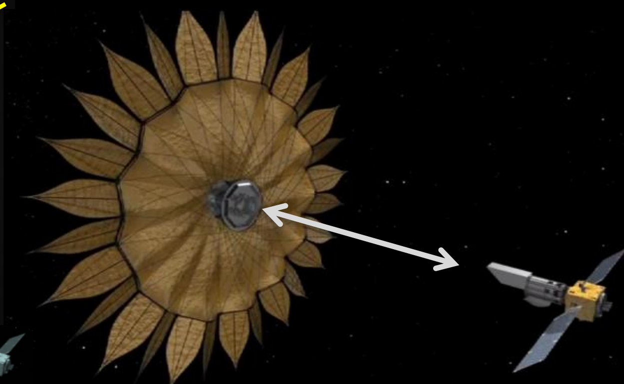
Starshade Technology Needs

Starlight Suppression

S-1: Controlling Scattered Sunlight



Formation Sensing and Control

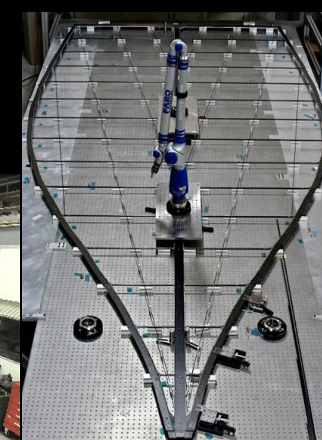


S-3: Lateral Formation Sensing

S-2: Starlight Suppression and Model Validation

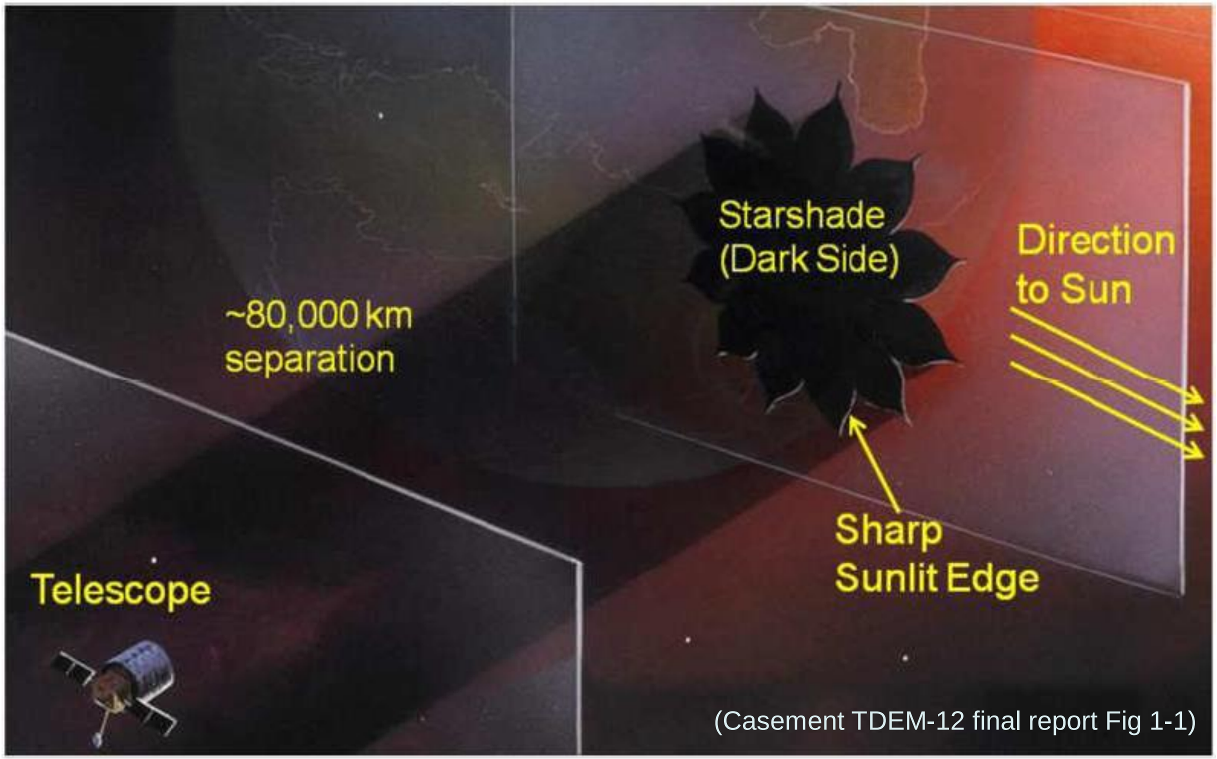
Deployment Accuracy and Shape Stability

S-5: Petal Positioning Accuracy and Opaque Structure



S-4: Petal Shape And Stability

Gap S-1: Controlling Scattered Sunlight



(Casement TDEM-12 final report Fig 1-1)

- **Exo-S study: Key parameters for Starshade edges:**
  1. Edges must maintain < 20 μm rms in-plane profile
  2. product of edge radius-of-curvature and reflectivity must be < 10 μm - %
- **Note: this spec is starshade size-independent, i.e. relevant for a WFIRST rendezvous-type mission and a HabEx or LUVOIR starshade**

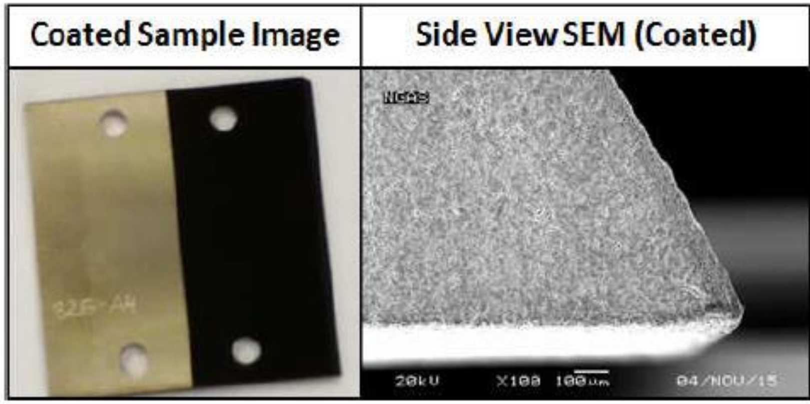
Priority	ID	Title	Description	Current Capabilities	Needed Capabilities
1	S-1	**Controlling Scattered Sunlight**	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (≥ 10 μm); etched metal edges meet all specs but in-plane shape tolerance (Exo-S design).	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limit solar glint contributing < 10^{-10} contrast at petal edges.

(ExEP Tech Plan Appendix Table 4)

Past Investments in Scattered Light Control

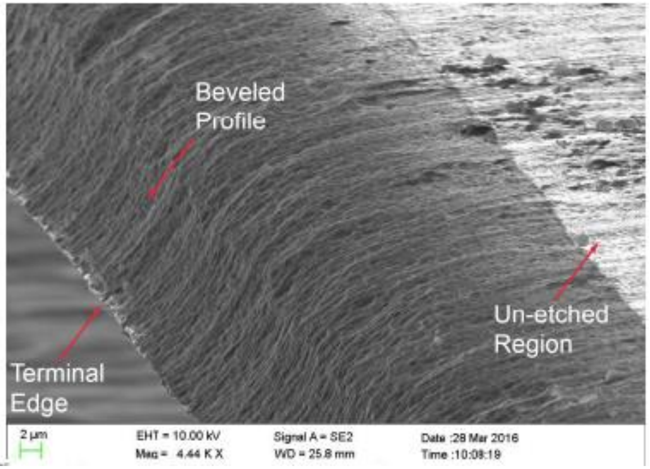
- **Exo-S study**
  - Optical models, including diffraction

- **Competed NASA SAT/TDEM award: Casement TDEM-2012**
  - Metal edge material with low-reflectivity coatings meets RoC-reflectivity reqt., robust to environmental tests



(Casement TDEM-12 final report Fig 1-3)

- **JPL internal funding**
  - Chemical-etched amorphous metal coupons meets RoC-reflectivity requirement, internal stress re-distribution issues remain
  - Stealth edge concept (requires 3-axis stabilized spacecraft)



Starshade Readiness Working Group (SSWG)

- **SSWG's briefing to NASA Astrophysics Division Director in November 2016 stated that overall, a ground validation approach to a starshade mission is sufficient**
  - The mitigation of scattered Sun light off the petal edges can be demonstrated through extensive lab scatter testing of small and full-scale samples

- **SSWG recommended a definition for TRL-5 for all Starshade technology needs.**

For Scattered Sunlight Control:

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			
	Scattered Sunlight						
Contrast	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	

(Deployment,
thermal cycles
Temperature,
humidity
Stowed strain)

Current / Future Investments

- **Phase II SBIR 2016: Tendeg, LLC "Robust Optical Edge for a Starshade Petal"**
- **Starshade Technology Development Activity**
- **Ongoing work at JPL:**
  - New etch process to mitigate deformation, allowing manufacturing of longer edge samples
  - Evaluation of dust sensitivity
- **Note: because of the creation of the Starshade Technology Development Activity, SAT/TDEM proposals for starshade currently not accepted**

Going forward: how ExEP can help

- **Ensure starshade technology development is appropriately prioritized through ExEP's annual Technology Selection and Prioritization Process**
- **Support development of the Starshade Technology Development plan**
- **Support ongoing mission concepts that could potentially include a Starshade component:**
  - WFIRST Starshade accommodation
  - Starshade Probe Study
  - HabEx and LUVOIR Decadal Survey Flagship studies