Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology Development Activity (S5)

Technology Development Plan and Science Mission Drivers

Phil Willems, S5 Manager

Kendra Short, ExEP Deputy Manager

Key Messages

- The requirements and milestones of the S5 Technology Development Plan are driven by the needs of the Science Mission Concepts
- The timing of the milestones is driven to support the Astro 2020 Decadal Survey
- We expect and have planned for evolution in the S5 project to respond to the changing needs of the mission concepts

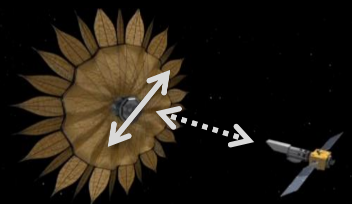
Background and Introduction

- 2010 Decadal report recommended investments in “starlight suppression techniques” for imaging and spectroscopy missions.
- NASA/APD utilized competitively selected awards issued under the Astrophysics Research and Analysis (APRA) and Strategic Astrophysics Technology (SAT) to address the starlight suppression needs identified in the ExEP Technology Gap List.
- In 2016, ExEP proposed a consolidated approach to starshade technology development to make sustained progress with the intent to:
  1. provide a more mature technology readiness level to the Astro 2020 Decadal Committee
  2. reach TRL5 on a timeframe to be ready for possible infusion into a near term mission, if endorsed by the Decadal Committee.
- The planning phase of S5 (starshade technology development to TRL 5) included:
  - community workshops to revalidate the starshade Technology Gaps.
  - technical trade study to evaluate the two viable mechanical architectures
  - reviews of the technical requirements, TRL 5 definition and demonstration milestones.

Starshade Technology Development Activity (S5)

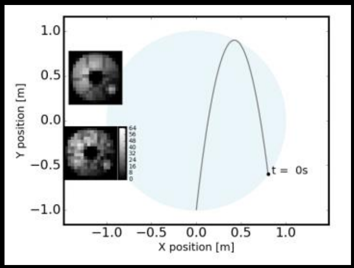
advance starshade technology to TRL 5 to enable future missions

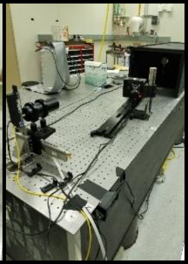
Formation Flying



+/- 30 cm sensing accuracy
+/- 1 m control

Testbed validated model of sensing accuracy; simulated control performance under flight-like conditions.

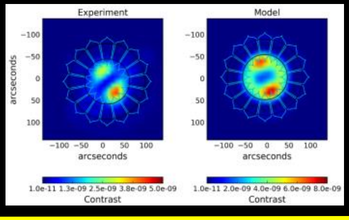




TGL S-3

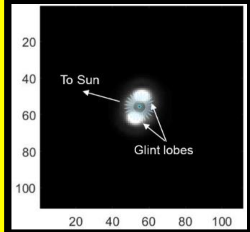
Starlight Suppression

Subscale demonstration of 1e-10 contrast at both narrow and broadband; optical model validation to 25% accuracy.

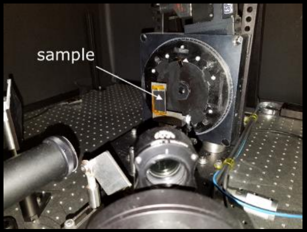


TGL S-1

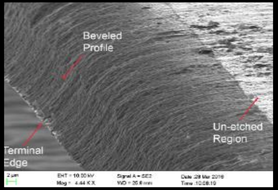
Scattered Sunlight



TGL S-2



Amorphous Metal

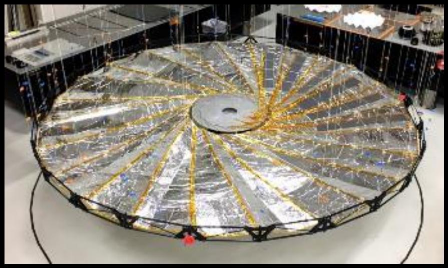


Scatterometer measurements of half-scale petal edge segments show scattered sunlight less than Vmag 25 in image simulations.

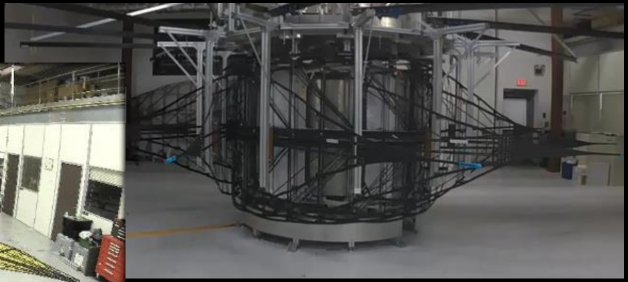
Mechanical Shape Accuracy/Stability
Mechanical Position Accuracy/Stability

Fabricate petals shape to a pre-launch accuracy of +/- 70um
Demonstrate by analysis an on-orbit shape stability of +/- 80um

Perform petal deployment to a position accuracy of +/- 300um
Demonstrate by analysis on-orbit position stability to +/- 200 um



TGL S-4 TGL S-5



TGL S-# is the ExEP Technology Gap List reference number

Evolution and Review of S5 Requirements

WFIRST / Starshade Rendezvous Mission (SRM)

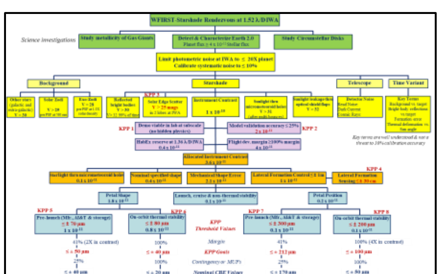
Habitable Exoplanet Observer Mission (HabEx)

Science Objectives
Measurement Thresholds
Calibration
Astrophysical Parameters

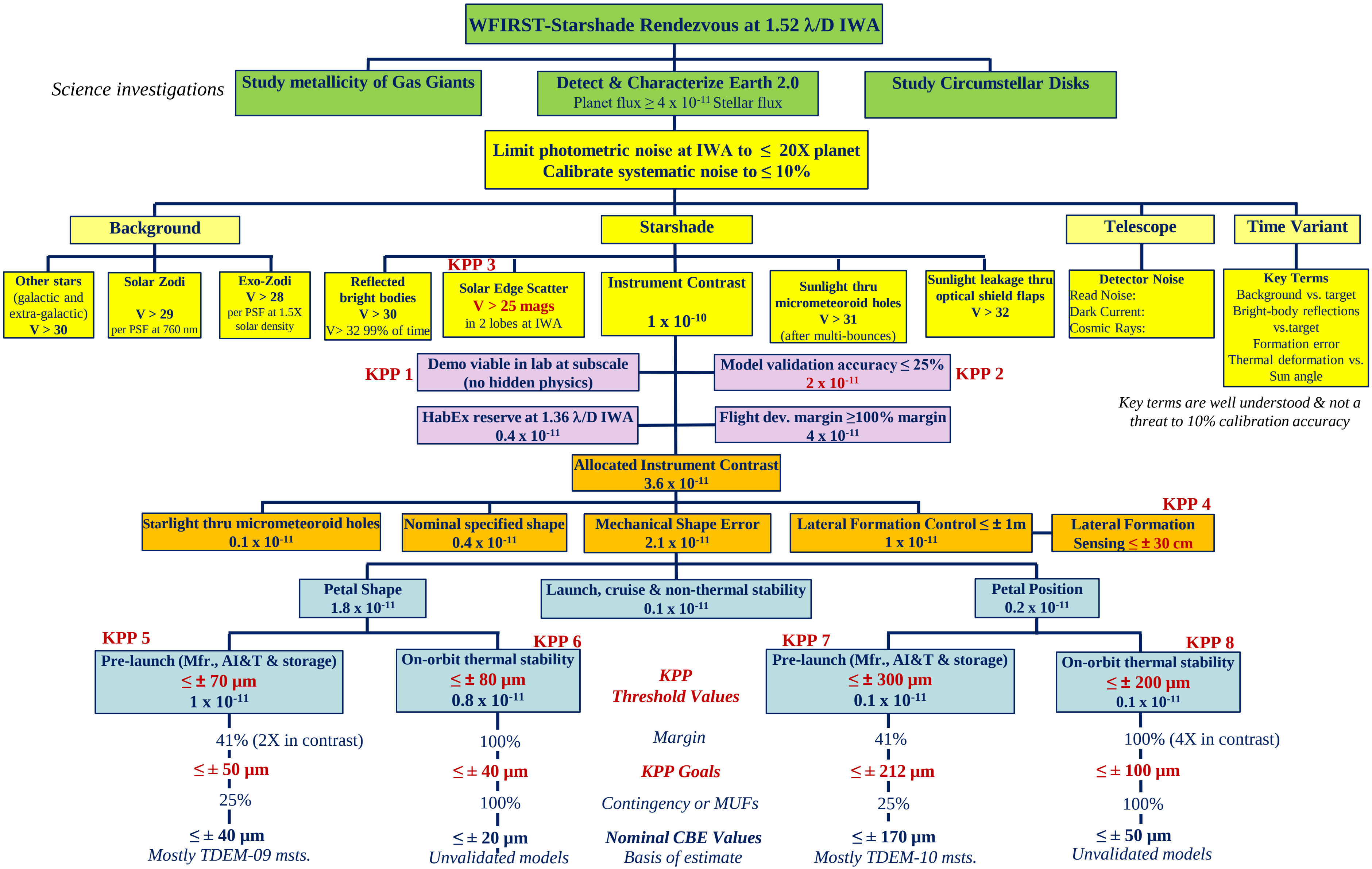
ExEP Technology Program

Technology Gaps (5)
Key Performance Parameters (8)

Science Performance Error Budget



S5 Error Budget Tree



Evolution and Review of S5 Requirements

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ExEP Technology Program

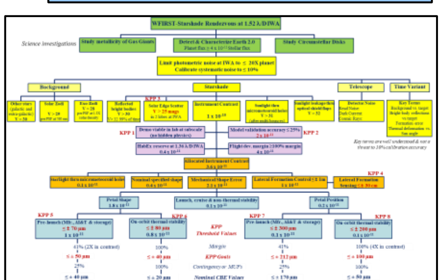
NASA NPR 7123.5 Appendix E

Nominal system design
Interfaces
Relevant environments

TRL Definitions
Exit Criteria

Science Performance Error Budget

TRL Definition for Starshade System and Elements



Technology Gap Area	KPP	Fidelity			Relevant Environments	Verification	Model Validation
		Form	Fit	Function			
Starlight Suppression	Demonstrate flight instrument contrast is viable via subscale lab tests at **≤ 1 x 10⁻¹⁰**	Flight-like shape, etched in silicon	1/500th scale, near-flight Fresnel #	Flight-like diffraction perf.	Space, large telescope distance	Measure image plane contrast at multiple wavelengths covering flight bandpass.	Demonstrates all physics are captured
	Validate contrast sensitivity to accuracy of ≤ ± **25%**					Introduce precisely known shape errors, measure contrast at the 10^{-8} to 10^{-9} level, extrapolate to flight contrast.	Validates model used to establish all shape error allocations
Lateral formation sensing & control	Verify sensing accuracy to **≤ ± 30 cm** (1/8th pupil dia.) & corresponding control to **≤ ± 1m**, via simulation	Flight-like shape, copper on glass	1/4000th scale, near-flight Fresenel #	Flight-like diffraction perf.	Space, large telescope distance, ≤ 1 μg gravity gradient	Measure lateral shear in pupil plane of Poisson spot from out of band starlight. Verify control perf. via simulations using a validated sensor model.	Validates prototype lateral sensor algorithms.
Solar Scatter	Verify lobe brightness is dimmer than **25 visual magnitudes**	Medium fidelity optical edge segment	3/4 scale	Flight-like scatter perf., in-plane shape profile accuracy	Deploy cycles, thermal cycles, dust in lab & launch fairing	Measure scatter at discrete Sun angles & measure in-plane profile, after env. Tests	Validates model of scatter vs. Sun angle at edge coupon level.
Petal Shape	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 70 μm**	Med. fidelity Petal Subsystem, all features & interfaces	3/4 scale	Flight-like	Deploy cycles, thermal cycles, stowed storage, temperature	Measure shape before & after env. tests,	Validates models of shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-orbit thermal stability **≤ ± 80 μm**					Measure petal critical dimensions in ambient press. "hot box" vs. temperature	
Petal Position	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 300 μm**	Med. fidlity Inner Disk Subsystem, all features & interfaces	Full-scale	Flight-like	0-gravity, space vacuum, stowed storage, temperature	Measure petal position after many quasi-static deployments that min. air drag and imperfect gravity off-loading.	Validates models of shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-orbit thermal stability **≤ ± 200 μm**					Measure Truss-Bay critical dimensions in ambient press. "hot box" vs. temperature	

S5 Key Performance Parameters

Technology Gap Area	KPP	Fidelity			Relevant Environments	Verification	Model Validation
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Starlight Suppression	Demonstrate flight instrument contrast is viable via subscale lab tests at **$\leq 1 \times 10^{-10}$**	Flight-like shape, etched in silicon	$1/500^{th}$ scale, near-flight Fresnel #	Flight-like diffraction perf.	Space, large telescope distance	Measure image plane contrast at multiple wavelengths covering flight bandpass.	Demonstrates all physics are captured
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The combination of the KPP performance specification and the TRL 5 expectations form the basis for the definitions for comprehensive Technology Milestone demonstrations.

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ExEP Technology Program

NASA NPR 7123.5 Appendix E

Available Budget Profile

Nominal system design
Interfaces
Relevant environments

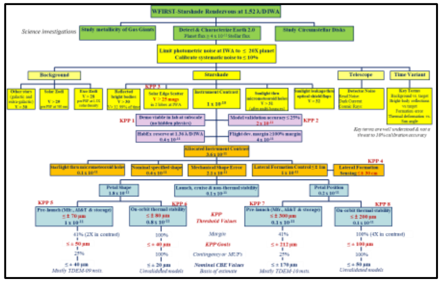
TRL Definitions
Exit Criteria

Milestone dates

Science Objectives
Measurement Thresholds
Calibration
Astrophysical Parameters

Technology Gaps (5)
Key Performance Parameters (8)

Science Performance Error Budget → **TRL Definition for Starshade System and Elements** → **S5 Technology Development Milestones**



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Lateral formation sensing & control	Verify sensing accuracy to **$\leq \pm$ 30 cm** (1/8th pupil dia.) & corresponding control to **$\leq \pm$ 1m**, via simulation	Flight-like shape, copper on glass	1/4000th scale, near-flight Fresenel #	Flight-like diffraction perf.	Space, large telescope distance, $\leq$ 1 µg gravity gradient	Measure lateral shear in pupil plane of Poisson spot from out of band starlight. Verify control perf. via simulations using a validated sensor model.	Validates prototype lateral sensor algorithms.
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Petal Shape	Pre-launch shape accuracy (manufacture, AI&T, storage) **$\leq \pm$ 70 µm**	Med. fidelity Petal Subsystem, all features & interfaces	3/4 scale	Flight-like	Deploy cycles, thermal cycles, stowed storage, temperature	Measure shape before & after env. tests.	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-orbit thermal stability **$\leq \pm$ 80 µm**					Measure petal critical dimensions in ambient press. "hot box" vs. temperature	
Petal Position	Pre-launch shape accuracy (manufacture, AI&T, storage) **$\leq \pm$ 300 µm**	Med. fidlity Inner Disk Subsystem, all features & interfaces	Full-scale	Flight-like	0-gravity, space vacuum, stowed storage, temperature	Measure petal position after many quasi-static deployments that min. air drag and imperfect gravity off-loading.	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-oribt thermal stability **$\leq \pm$ 200 µm**					Measure Truss-Bay critical dimensions in ambient press. "hot box" vs. temperature	

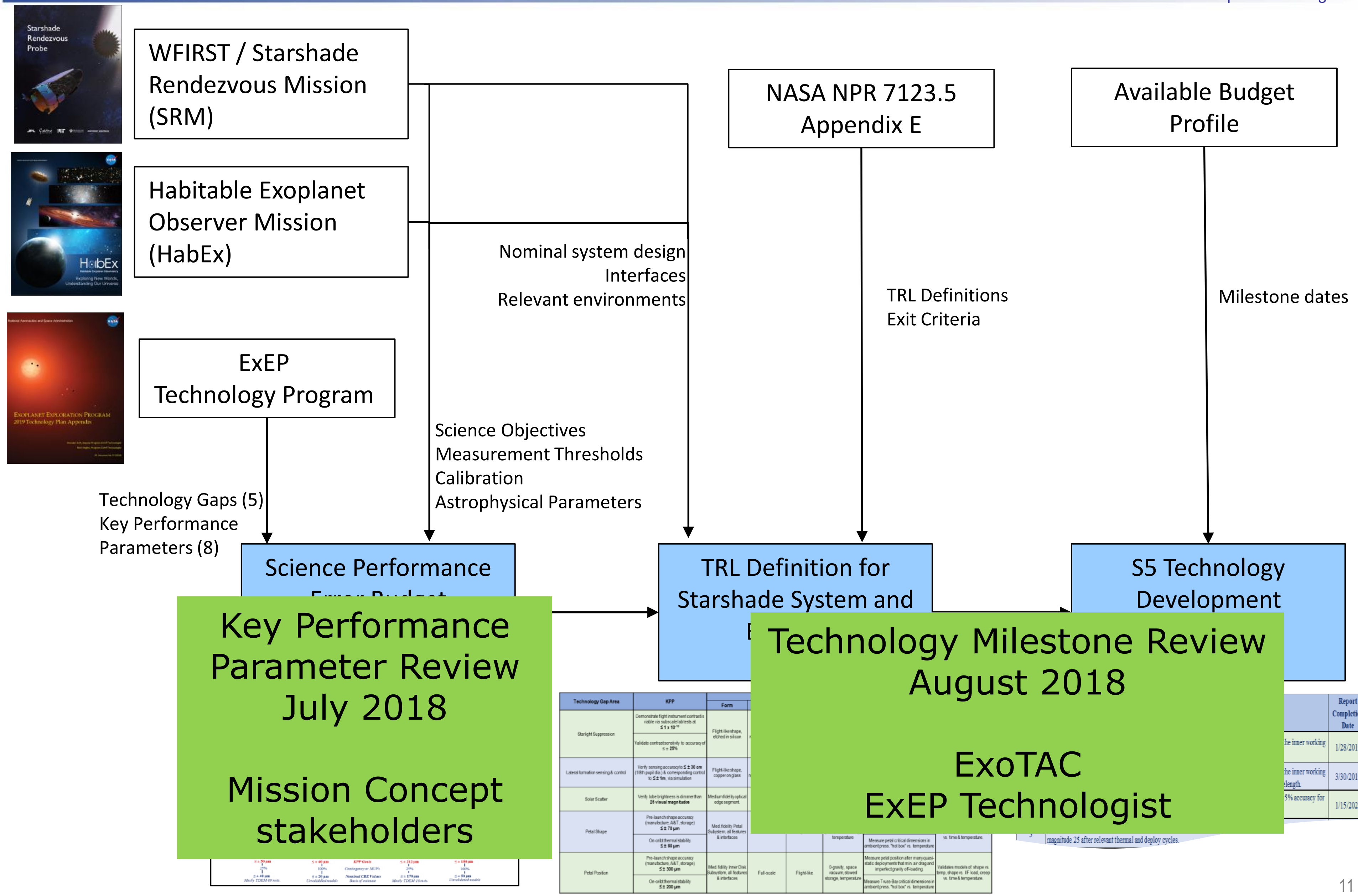
MS #	Milestone	Report Completion Date
1A	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle in narrow band visible light and Fresnel number $\leq$ 15.	1/28/2019
1B	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning $\geq$ 10% bandpass at Fresnel number $\leq$ 15 at the longest wavelength.	3/30/2019
2	Small-scale starshade masks in the Princeton Testbed validate contrast vs. shape model to within 25% accuracy for induced contrast between 10^{-9} and 10^{-8}.	1/15/2020
3	Optical edge segments demonstrate scatter performance consistent with solar glint ... magnitude 25 after relevant thermal and deploy cycles.	

S5 Key Technology Milestones

	MS #	Milestone	Report Completion Date
Starlight Suppression S-2	1A	Small-scale starshade mask in the Princeton Testbed demonstrates 1x10^{-10} instrument contrast at the inner working angle in narrow band visible light and Fresnel number ≤ 15.	1/28/2019
	1B	Small-scale starshade mask in the Princeton Testbed demonstrates 1x10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning ≥ 10% bandpass at Fresnel number ≤ 15 at the longest wavelength.	3/30/2019
	2	Small-scale starshade masks in the Princeton Testbed validate contrast vs. shape model to within 25% accuracy for induced contrast between 10^{-9} and 10^{-8}.	1/15/2020
Scattered Sunlight S-1	3	Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.	11/1/2019
Formation Flying S-3	4	Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral offset position accuracy to a flight equivalent of ± 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.	11/14/2018
Petal Position and Shape: Accuracy and Stability S-4, S-5	5A	Petal subsystem with *shape critical features* demonstrates shape stability after deploy cycles and thermal cycles (deployed) consistent with a total pre-launch shape accuracy within ± 70 µm.	12/20/2019
	5B	Petal subsystem with *all features* demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, & storage) to within ± 70 µm.	6/2/2023
	6A	Petal subsystem with *shape critical features* demonstrates on-orbit thermal stability within ± 80 µm by analysis using a validated model of critical dimension vs. temperature.	12/20/2019
	6B	Petal subsystem with *all features* demonstrates on-orbit thermal stability within ± 80 µm using a validated model of critical dimension vs. temperature.	6/2/2023
	7A	Truss Bay *longeron and node subassemblies* demonstrate dimensional stability with thermal cycles (deployed) consistent with a total pre-launch petal position accuracy within ± 300 µm. (Note: SBIR funding dependency)	12/20/2019
	7B	Truss Bay *assembly* demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ± 300 µm.	6/2/2023
	7C	Inner Disk Subsystem with optical shield assembly that includes *deployment critical features* demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 µm. (Note: SBIR funding dependency)	12/20/2019
	7D	Inner Disk Subsystem with optical shield assembly that includes *all features* demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 µm.	6/2/2023
	8A	Truss Bay *longeron and node subassemblies* demonstrate on-orbit thermal stability within ± 200 µm by analysis using a validated model of critical dimension vs. temperature.	12/20/2019
	8B	Truss Bay *assembly* demonstrates on-orbit thermal stability within ± 200 µm by analysis using a validated model of critical dimension vs. temperature.	6/2/2023

Evolution and Review of S5 Requirements

ExoPlanet Exploration Program



Key Performance Parameter Review

- KPP peer review was held on July 25, 2018 with mission stakeholders and technical experts to evaluate the proposed KPPs and how they flow-down from science requirements
- Key findings and responses are summarized in the table below

"The peer review went well, with the panel largely endorsing the KPPs as outlined by the S5 team. The one major source of uncertainty in their comments had to do with the solar scatter KPP requirement and the two 'lobes' of sunlight glint" – Peer Review Memo

#	Findings/Comments	Response/Status
1	Model validation uncertainty applies to all contrast errors, not just shape errors, as shown.	The error budget and KPPs have been modified accordingly
2	Calibrating solar glint to within 1% accuracy may not be possible.	We now assume a small loss in detection space at the IWA, which relaxes the required calibration accuracy to 10%. Assessments by the mission study teams are in progress.
3	Time variant noise terms belong in the error budget.	A placeholder is added to the error budget but values are TBD. We do not expect any change to the KPPs.
4	IDS-OS prototype plans do not include integrating solar cells as required for Habex to support SEP.	An existing SBIR Phase 2 activity will develop and test a proof of concept IDS-OS with solar cells. Carrying this forward to TRL-5 is carried as a risk item.
5	Are error budget margins sufficient ?	Margins presented at milestone review to ExoTAC in more detail and the TAC concurs. The KPP reviewer also concurs.
6	Should update analyses of stray light, including micrometeoroid holes.	Analysis updates are planned in FY19.

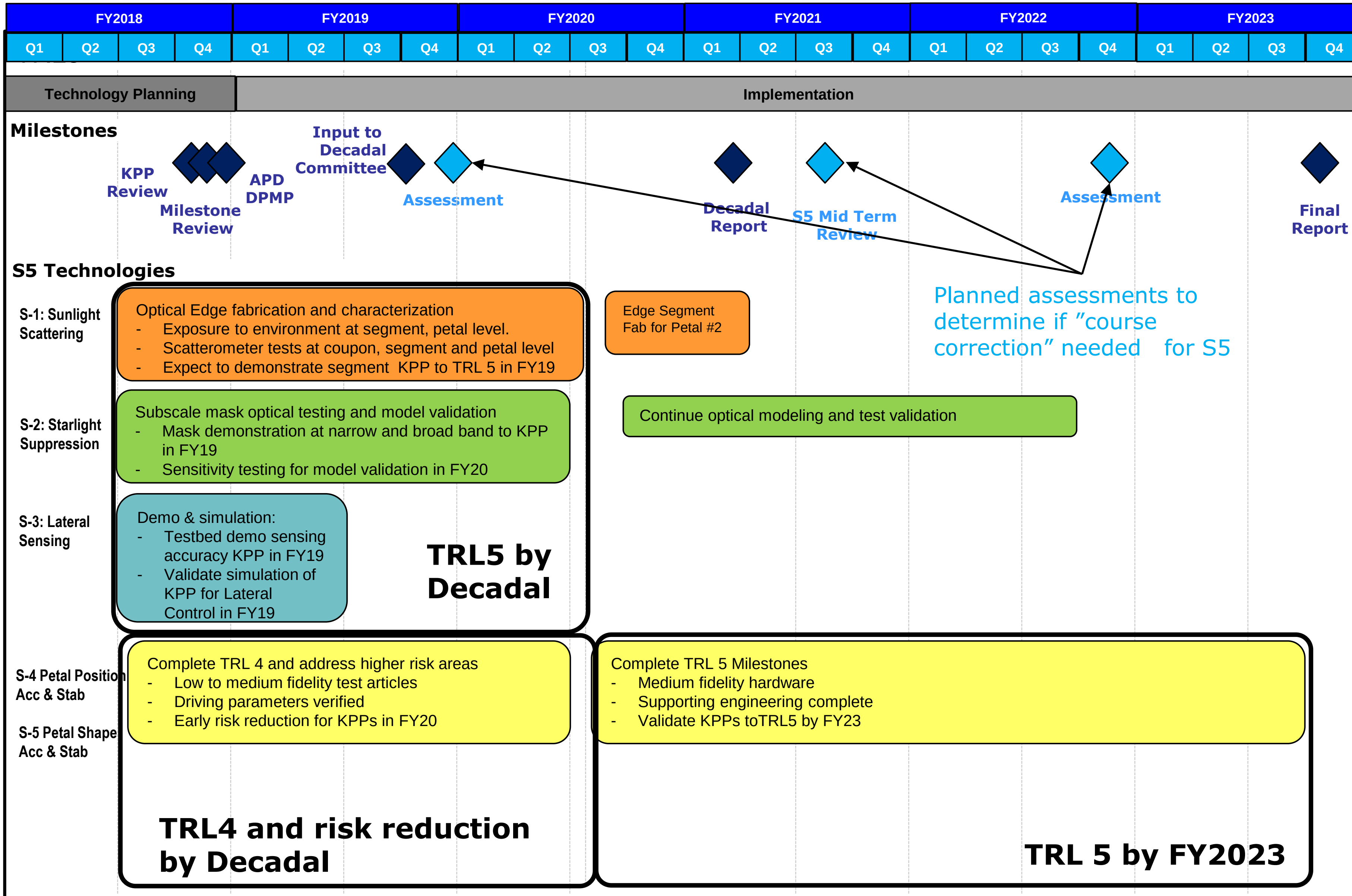
Technology Milestone Review

- A technology milestone review was held on August 7, 2018 with the ExoTAC plus Feng Zhao and Nick Siegler to evaluate the proposed milestones, how they flow-down from the KPPs, how they lead to TRL-5 and the verification plans
- Key findings and intended responses are summarized in the table below

"In summary, the TDP Milestones presented are an impressive, compelling, well-designed suite that will advance the technological readiness of the starshade concept for WFIRST or other future missions (e.g., HabEx), allowing starshades to be properly evaluated and ranked by Astro 2020." – ExoTAC report

#	Findings/Comments	Response/Status
1	The TAC would like to learn about the collection of small shape error terms that are not detailed.	The TAC will be provided a package detailing these small shape errors (completed as part of Mech Trade activity). The S5 assessment that no additional integration time or calibration is required will be provided for consideration.
2	Does characterizing Earth 2.0 require additional planet contrast beyond the 4×10^{-11} specified ?	Detecting spectral features can be thought of as requiring additional contrast relative to the continuum. Instead, the science teams have specifid high SNR levels (e.g., 20 to detect H_2O and O_2) that is equivalent to specifying that we can detect 5% 1σ variations in the continuum. This response will be documented and iterated with the orginator (Rebecca Oppenheimer)
3	The TAC concurs with categorizing the Deployment Control System (DCS, aka PLUS) as an engineering development, but recommends: 1) DCS development plans are moved to the main body of this presentation and 2) DCS status is reported as part of milestone reports.	The final presentation package has been modiified to include DCS plans in the main body. A Level 1 deliverable report for the DCS has been added to the baseline plan and appears on the top tier schedule (interim and final).

FY18-FY23 Schedule – S5 Activities

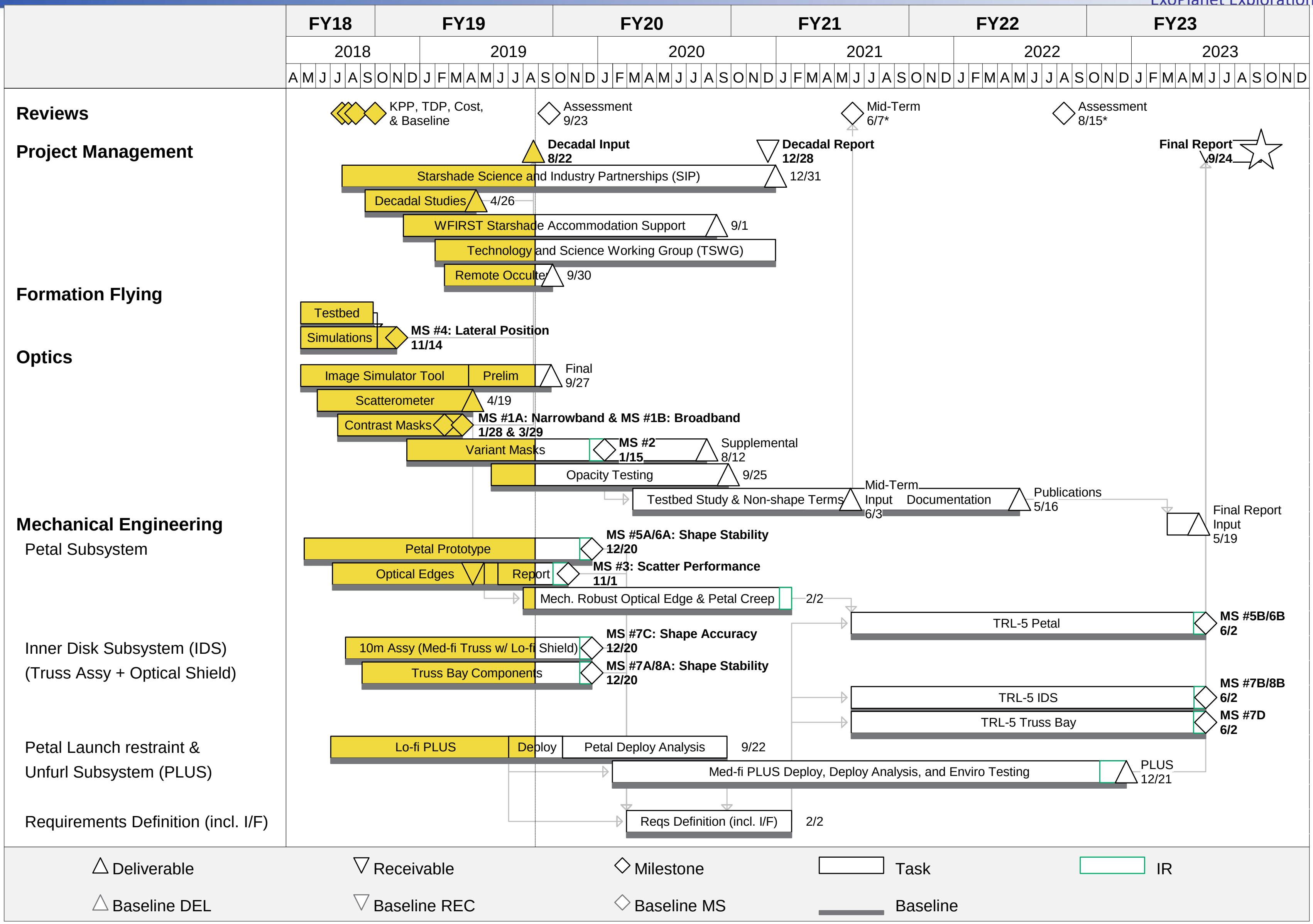


Starshade Technology Development Activity to TRL-5 (S5)

Tier 1 Schedule

8/25/2019

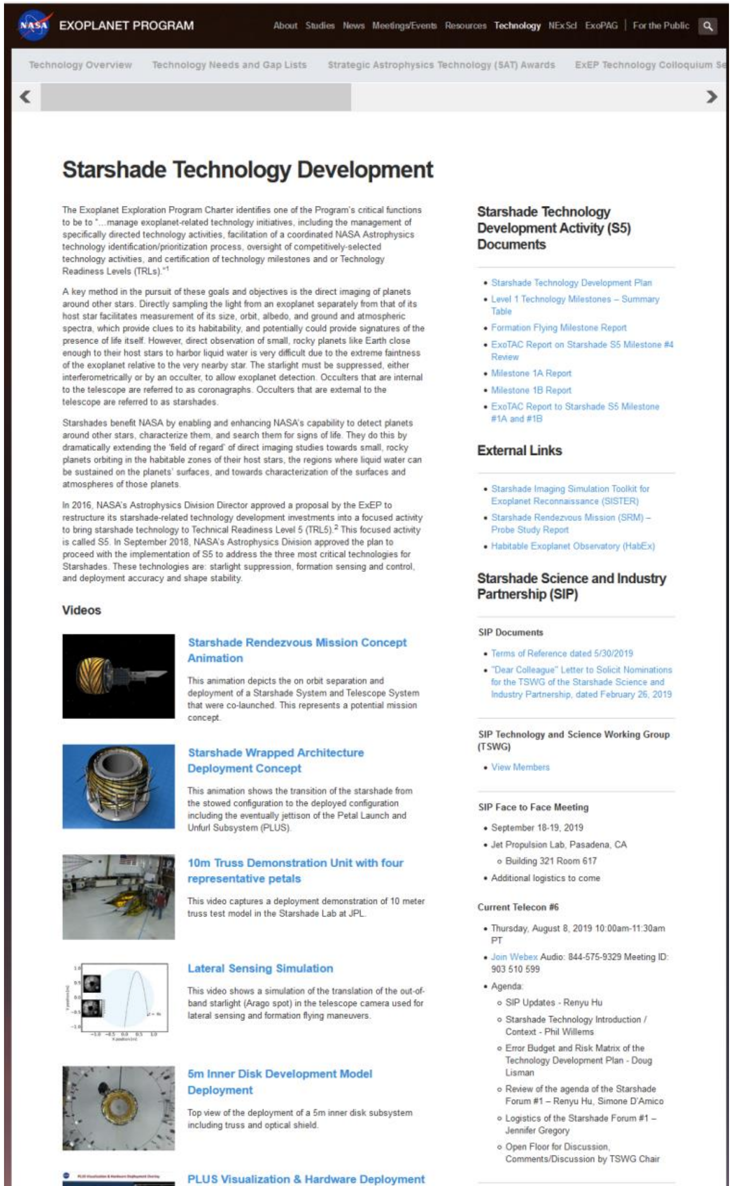
ExoPlanet Exploration Program



Information To Support Astro 2020

- Key Resources:
  - S5 Technology Development Plan
  - Milestone Reports
  - APC White Paper – Purpose and Mission Concept Synergy for S5
  - S5 Technology Status (as of) August 2019

Public Dissemination of S5 Results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Starshade Technology Development

The Exoplanet Exploration Program Charter identifies one of the Program's critical functions to be to "...manage exoplanet-related technology initiatives, including the management of specifically directed technology activities, facilitation of a coordinated NASA Astrophysics technology identification/prioritization process, oversight of competitively-selected technology activities, and certification of technology milestones and or Technology Readiness Levels (TRLs)."[1]

A key method in the pursuit of these goals and objectives is the direct imaging of planets around other stars. Directly sampling the light from an exoplanet separately from that of its host star facilitates measurement of its size, orbit, albedo, and ground and atmospheric spectra, which provide clues to its habitability, and potentially could provide signatures of the presence of life itself. However, direct observation of small, rocky planets like Earth close enough to their host stars to harbor liquid water is very difficult due to the extreme faintness of the exoplanet relative to the very nearby star. The starlight must be suppressed, either interferometrically or by an occulter, to allow exoplanet detection. Occulters that are internal to the telescope are referred to as coronagraphs. Occulters that are external to the telescope are referred to as starshades.

Starshades benefit NASA by enabling and enhancing NASA's capability to detect planets around other stars, characterize them, and search them for signs of life. They do this by dramatically extending the 'field of regard' of direct imaging studies towards small, rocky planets orbiting in the habitable zones of their host stars, the regions where liquid water can be sustained on the planets' surfaces, and towards characterization of the surfaces and atmospheres of those planets.

In 2016, NASA's Astrophysics Division Director approved a proposal by the ExEP to restructure its starshade-related technology development investments into a focused activity to bring starshade technology to Technical Readiness Level 5 (TRL5).[2] This focused activity is called S5. In September 2018, NASA's Astrophysics Division approved the plan to proceed with the implementation of S5 to address the three most critical technologies for Starshades. These technologies are: starlight suppression, formation sensing and control, and deployment accuracy and shape stability.

Videos

Starshade Rendezvous Mission Concept Animation

This animation depicts the on orbit separation and deployment of a Starshade System and Telescope System that were co-launched. This represents a potential mission concept.

Starshade Wrapped Architecture Deployment Concept

This animation shows the transition of the starshade from the stowed configuration to the deployed configuration including the eventually jettison of the Petal Launch and Unfurl Subsystem (PLUS).

10m Truss Demonstration Unit with four representative petals

This video captures a deployment demonstration of 10 meter truss test model in the Starshade Lab at JPL.

Lateral Sensing Simulation

This video shows a simulation of the translation of the out-of-band starlight (Arago spot) in the telescope camera used for lateral sensing and formation flying maneuvers.

5m Inner Disk Development Model Deployment

Top view of the deployment of a 5m inner disk subsystem including truss and optical shield.

PLUS Visualization & Hardware Deployment

Starshade Technology Development Activity (S5) Documents

- Starshade Technology Development Plan
- Level 1 Technology Milestones – Summary Table
- Formation Flying Milestone Report
- ExoTAC Report on Starshade S5 Milestone #4 Review
- Milestone 1A Report
- Milestone 1B Report
- ExoTAC Report to Starshade S5 Milestone #1A and #1B

External Links

- Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)
- Starshade Rendezvous Mission (SRM) – Probe Study Report
- Habitable Exoplanet Observatory (HabEx)

Starshade Science and Industry Partnership (SIP)

SIP Documents

- Terms of Reference dated 5/30/2019
- "Dear Colleague" Letter to Solicit Nominations for the TSWG of the Starshade Science and Industry Partnership, dated February 26, 2019

SIP Technology and Science Working Group (TSWG)

- View Members

SIP Face to Face Meeting

- September 18-19, 2019
- Jet Propulsion Lab, Pasadena, CA
  - Building 321 Room 617
- Additional logistics to come

Current Telecon #6

- Thursday, August 8, 2019 10:00am-11:30am PT
- Join Webex Audio: 844-575-9329 Meeting ID: 903 510 599
- Agenda:
  - SIP Updates - Renyu Hu
  - Starshade Technology Introduction / Context - Phil Willems
  - Error Budget and Risk Matrix of the Technology Development Plan - Doug Lisman
  - Review of the agenda of the Starshade Forum #1 – Renyu Hu, Simone D'Amico
  - Logistics of the Starshade Forum #1 – Jennifer Gregory
  - Open Floor for Discussion, Comments/Discussion by TSWG Chair

- Provide a Starshade Technology web-page within the ExEP web portal*

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

- Provides the following data types:
  - S5 Technology Development Plan
  - Milestone Reports and ExoTAC Reviews
  - Forum Presentations (webex and F2F)
  - Links to relevant publications and webpages
  - Starshade graphics, videos and other materials
- All content subject to ITAR review for unlimited release.

- Publish milestone results in technical journals and present at conferences.

S5 Guiding Principles

- Be broad based in the applicability of the technology to various mission concepts and scales.
- Be ready for 2020 Astrophysics Decadal Survey (submission in Summer 2019)
  - Technologies need to be mature enough to enable a possible starshade to be considered for near term opportunities and future large telescope missions
  - Early technical progress in starlight suppression, scattered sunlight, and formation flying, coupled with steady progress toward later mechanical TRL5 milestones through early demonstration and risk reduction activities in deployable structures.
- Confident validation of our models and requirements through sub-scale testing
  - Error budget requirements developed and performance verification through validated models (optical diffraction, scattering, mechanical, thermal, dynamics, etc.) and test.
- Independent reviews of our technology plan, technical progress, and milestones. Open dissemination of results through Technology Reports, peer reviewed publications.
- Open and engaging with the science community and partners - flexibility to changes in environment, ideas and knowledge.