Astro2020 APC Whitepaper

NASA's Focused Starshade Technology Development and its Synergy with Future Mission Concepts

Principal Author:

Kendra Short
NASA/JPL/Caltech
kendra.l.short@jpl.nasa.gov

Co-authors:

Phil Willems (NASA/JPL/Caltech), Doug Lisman (NASA/JPL/Caltech), Renyu Hu (NASA/JPL/Caltech), Stuart Shaklan (NASA/JPL/Caltech), Thibault Flinois (NASA/JPL/Caltech), Michael Bottom (NASA/JPL/Caltech), David Webb (NASA/JPL/Caltech), Stefan Martin (NASA/JPL/Caltech)

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INTRODUCTION

NASA is poised today as never before to make starshades a reality as a result of the advancement of critical technology. This white paper presents a description of the focused investments in Starshade Technology that the NASA Astrophysics Division is making through the dedicated technology development activity known as "Starshade Technology to TRL 5" (aka S5). This activity is managed by the Exoplanet Exploration Program, a thematic program within NASA/APD to support its exoplanet exploration objectives. The S5 activity is intentionally structured to mature the required technologies to the point at which starshades could be integrated into potential future exoplanet detection and characterization missions. In other words, bring all technologies to a Technology Readiness Level of 5 (Ref 1) through a purposeful development and test program. Several of the mission concepts currently funded by APD assume a starshade, specifically the probe class study Starshade Rendezvous Probe Mission with WFIRST (SRM) (Ref 10) and the Habitable Exoplanet Observatory (HabEx), a large mission study (Ref 11). The S5 is deliberate in its synergy with the mission concepts defined today, but S5 is also expected to evolve if necessary to support the future needs of concepts just being envisioned. This whitepaper provides an overview of the origins of the S5 activity, the baseline development plan and the concerted efforts to define performance requirements and technology readiness levels consistent with the needs of representative mission concepts such as the SRM and HabEx. Progress against the defined technology milestones will be summarized only briefly here to convey the successes to date. A more thorough technical progress report on S5 will be delivered later in the fall to the Decadal Committee by NASA/APD. Lastly, this paper will describe the explicit activities within the S5 project, such as community engagement and planned assessment reviews, to keep the program agile and responsive to the emerging needs of new mission concepts and capabilities.

Because this white paper is being submitted by NASA's Exoplanet Exploration Program Office it does not advocate for the scientific value of a particular mission concept, but instead describes how NASA intends to be ready to support the earliest possible need of any starshade mission that may be endorsed or established in the future.

WHY STARSHADES?

The 2014 NASA Strategic Plan has a Strategic Objective to "discover how the universe works, explore how it began and evolved, and search for life on planets around other stars."(Ref 2). 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 starshade, an external occulter, is used to suppress the starlight allowing the reflected light from the planet to be revealed. (Ref 3).

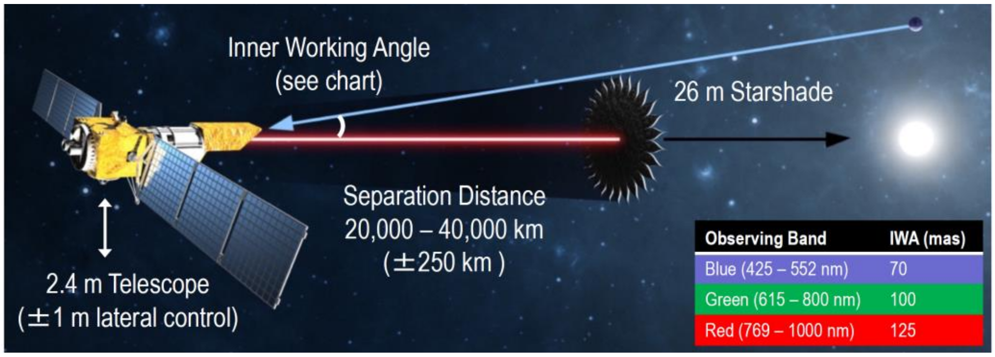

Figure 1 – Illustration depicting a telescope / starshade configuration.

Starshades suppress on-axis starlight by blocking the light with an apodized occulter that causes light diffracted around its edges to interfere destructively at the entrance pupil of a telescope, creating a deep shadow that is slightly larger than the telescope aperture to allow for slight errors in the starshade's position. The depth of the shadow is called "contrast". Contrast refers to the ratio of irradiance at an element in the image plane with the starshade in place, to the irradiance that would be seen at the same point if the star were centered there with no starshade. A circular occulter without apodization would produce a bright spot at the center of the shadow due to constructive interference of diffracted light, an effect known as Poisson's spot. This would ruin the ability to image faint exoplanets. The apodization is implemented by a ring of 'petals' surrounding the central obscuration disk, which cause the azimuthally averaged transmission profile of the starshade to vary in a smooth fashion from 0 to 100% from the base of the petals to their tips. The starshade must position itself to maintain the shadow on the telescope, and its petals must maintain a very precise shape to produce the desired reduction in starlight relative to the light from the exoplanet. It must also be opaque and limit the amount of sunlight scattered from the petal edges into the telescope (Ref 3).

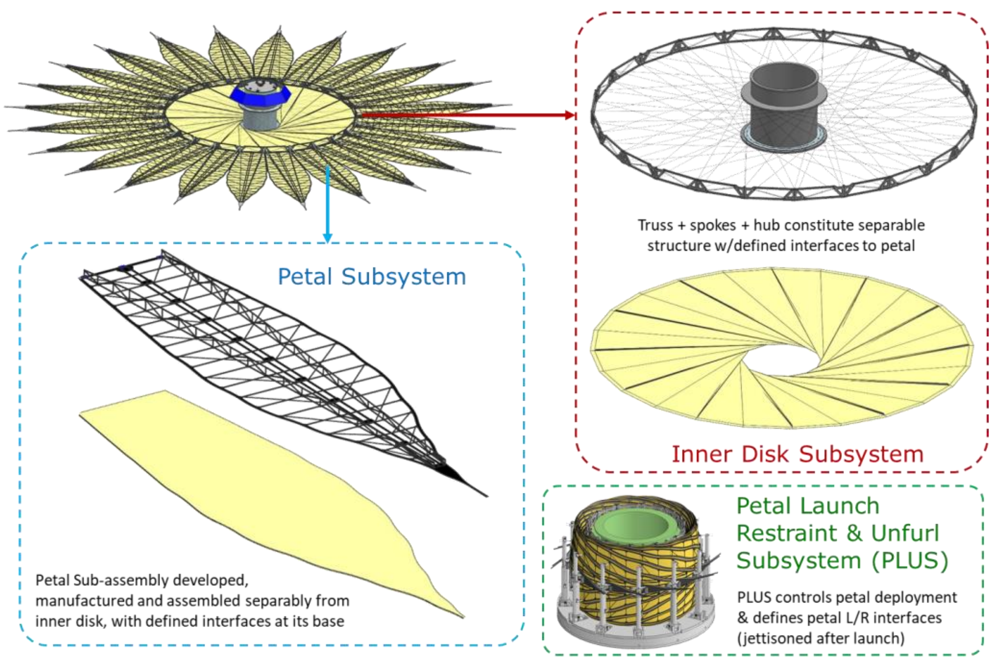

Figure 2 – Starshade mechanical elements: petals, inner disk, PLUS.

FOCUSED TECHNOLOGY DEVELOPMENT

Up until 2016, NASA/ExEP has funded community work on starshade technologies via competed grants within the Program's Technology Development for Exoplanet Missions (TDEM) funding line. 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 (S5) to bring starshade technology more quickly to Technical Readiness Level 5 (TRL5), with the goal to mature these technologies on a timescale to allow starshades to be integrated into potential future exoplanet detection and characterization missions (Ref 4). The critical technology "gaps" for starshades are identified in the ExEP Technology Plan (Ref 5) as starlight suppression, formation flying and mechanical deployment accuracy and shape stability. The S5 activity is directed to close the gap for formation flying and starlight suppression, and mature the associated technologies to TRL 5 by March 2020. For the mechanical accuracy and stability gap, S5 is directed to reach TRL4 for the associated technologies by March 2020 and TRL 5 by September 2023 (Ref 6). The timeframe of 2023 is chosen to be compatible with the earliest possible date a future mission might be able to pick up the mission specific development from TRL5 to 6 and beyond.

A Technology Development Plan (TDP) outlines both the technical objectives of the task as well as the management approach. The TDP breaks down the overarching requirement of imaging and characterizing an Earth-like planet into key performance specifications and distributes the contrast requirement, with margins, to the noise allowance of each component of the starshade. The TDP also captures the specific design baselines, the key performance specifications to meet, the assumptions behind TRL 5 (test article fidelity, relevant environments) and ultimately the fifteen milestones which comprise the success criteria of the activity (see Table 1). The complement of fifteen milestones were reviewed and approved by the Exoplanet Technology Assessment Committee (ExoTAC). The ExoTAC also reviews the S5 final Milestone Reports to provide independent certification that the milestone was sufficiently met. All materials generated by the S5 project can be found under the Exoplanet Exploration Program Starshade Technology web page (http://exoplanets.nasa.gov/exep/technology/starshade). Materials available on the website include the S5 TDP itself, all final Milestone Reports, as well as the ExoTAC memos documenting their review of the milestone completion and their findings.

STARSHADE TECHNOLOGY GAPS

The ExEP program aims to identify the technologies that will enable NASA's future exoplanet missions, and to facilitate their maturation to be ready when needed. These technologies are identified through technology gap lists and communicated through the annual Technology Plan Appendix. A technology gap is defined as the difference between what has been done (or is known) today relative to what is needed in order to implement a future mission, and candidate technologies are ones that potentially close the gap. For starshades, the ExEP Technology Plan Appendix lists three gaps of starlight suppression, formation flying and mechanical deployment accuracy and shape stability. Within these three gaps are five *technologies* that must be advanced. These five technologies are described below.

Starlight Suppression: The optical characteristics of the starshade must reduce light from the star by 10^{-10} in order to achieve the level necessary to detect an exo-Earth. The knowledge of which starshade shapes will suppress the exoplanet host star's light at the 10^{-10} level requires experimental validation. A validated model that includes all significantly contributing optical physics and correctly predicts variation of performance with change of shape at this performance level is a critical technology.

Sunlight Scatter: A significant source of noise from the starshade is due to the light from our own sun scattered off its edges. Edges that can limit scattered sunlight to acceptable levels is another critical technology.

Formation Sensing and Control: The ability to sense and control the lateral offset between the starshade and the telescope is necessary to maintain the desired contrast long enough for full science integration. The technology required to close this gap is a validated technique for sensing lateral displacements of the starshade from the line of sight between the telescope and exoplanet host star to the necessary precision and accuracy.

Deployment Accuracy and Shape Stability: The ability to manufacture, stow, launch, and deploy the starshade with a shape accuracy within the contrast requirements error budget is challenging. In addition, the final shape must be stable throughout on-orbit operational environments within an additional allocated error. The two key mechanical technologies within this mechanical technology gap are: (1) Petal Shape Accuracy and Stability – can a petal be manufactured, stored and deployed to the required shape accuracy and can its shape be maintained within allocated tolerances through-out on-orbit conditions. (2) Petal Position Accuracy and Stability – can the petals be deployed to the proper position accuracy and maintained in that position within allocated tolerances throughout on-orbit conditions.

Prior to completing the Technology Development Plan, S5 held many community workshops to verify whether these gaps/technologies identified in the Technology Gap List were the complete set of technologies to be addressed in S5 and what the state of each technology was. An open forum was held followed by focused workshops for each of the three areas with participants from government, academia and industry. In the end, no other technology gaps were identified.

SCOPE AND SUCCESS CRITERIA FOR S5

TECHNOLOGY MILESTONES = KEY PERFORMANCE PARAMETERS +TRL 5

The scope of the S5 activity necessary to close the technology gaps is captured in a set of 15 Technology Milestones which combine science driven performance requirements with the definition of TRL5. These milestones, which technology they address and the expected completion dates are provided in Table 1 below. Per NASA's NPR 7123.1 definitions of TRL, the critical aspects of TRL5 include demonstrating overall performance with medium fidelity (brassboard) test articles in a relevant (stressing) environment. The requirements for performance and environments are best defined in the context of a “design reference mission”. S5 takes the Starshade Rendezvous Mission (SRM) concept as its Design Reference Mission with the goal of being extensible to the more ambitious HabEx mission whenever possible. All key performance parameters derive ultimately from the contrast requirement for observing and characterizing Earth-like exoplanets. S5 worked with representatives of both SRM and HabEx to establish the science driven top level contrast requirement and flow that requirement into a comprehensive error budget. This error budget allocates acceptable contributions to the overall contrast level from each source in the background, errors in the telescope and in the starshade system to achieve the necessary contrast. The Key Performance Parameters for the starshade technology areas (labeled in red in Figure 2) define the performance levels to be demonstrated in the S5 milestones. The other aspects of TRL5 including test article/simulation fidelity and relevant environments are derived from the starshade system configuration and the SRM mission design.

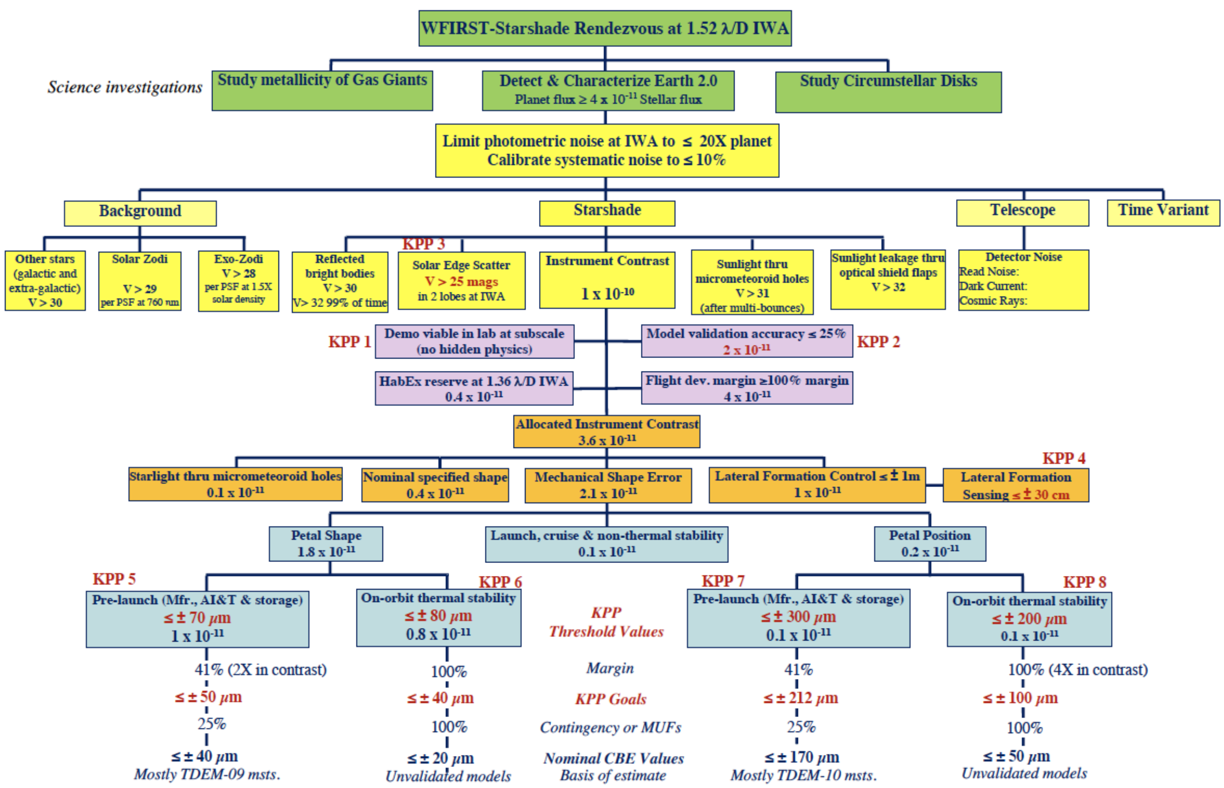

Figure 3: Flow down of requirements of Starshade Rendezvous mission to Key Performance Parameters of starshade technologies.

Table 1 – Technology Milestones for S5

Technology	Key Performance	MS#	Date	Milestone
Starlight Suppression	Contrast at Narrowband	1A	1/28/19	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 ≤ 15.
	Contrast at Broadband	1B	3/30/19	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning ≥ 10% bandpass at the Fresnel number ≤ 15 at the longest wavelength.
	Optical Model Validation	2	1/15/20	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}.
	Optical Edge Performance	3	11/1/19	Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.
Formation Flying	Lateral Sensing	4	11/14/18	Starshade Lateral Alignment Testbed validates sensor model by demonstrating lateral offset position accuracy to flight equivalent of ± 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.
Petal Shape	Pre-launch Shape Accuracy	5A	12/20/19	Petal subsystem with *shape critical features* demonstrates shape stability after deploy cycles (deployed) consistent with a total pre-launch shape accuracy within ± 70 μm.
	Pre-launch Shape Accuracy	5B	6/2/23	Petal subsystem with *all features* demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, and storage) to within ± 70 μm.
	On-orbit Thermal Stability	6A	12/20/19	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.
	On-orbit Thermal Stability	6B	6/2/23	Petal subsystem all *features* demonstrates on-orbit thermal stability within ± 80 μm by analysis using a validated model of critical dimension vs. temperature.
Petal Position	Pre-launch Position Accuracy	7A	12/20/19	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.
	Pre-launch Position Accuracy	7C	12/20/19	Inner Disk Subsystem with optical shield assembly that includes *deployment critical features* demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm.
	Pre-launch Position Accuracy	7D	6/2/23	Inner Disk Subsystem with optical shield assembly that includes *all features* demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm.
	Pre-launch Position Accuracy	7B	6/2/23	Truss Bay *assembly* demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ± 300 μm.
	On-orbit Thermal Stability	8A	12/20/19	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.
	On-orbit Thermal Stability	8B	6/2/23	Truss Bay *assembly* demonstrates on-orbit thermal stability within ± 200 μm by analysis using a validated model of critical dimension vs. temperature.

Although the S5 plan assumes the Rendezvous Mission with WFIRST in establishing its KPPs, article fidelities, and relevant environments, these are not tightly constrained by the current baseline WFIRST design. They would be generally applicable to any optical space telescope of similar aperture operating in an Earth-Sun L2 orbit, so long as it includes a pupil plane sensor consistent with the lateral position sensing concept. As for HabEx, the starshade KPPs for the HabEx mission are identical to those for Starshade Rendezvous Mission with one exception. The most significant difference between these two starshades would be their sizes: the WFIRST Rendezvous starshade would be about 26m in diameter, and the HabEx starshade about 52m. The error budget includes 4E-12 of reserve contrast to account for HabEx operating at 1.36 λ/D and therefore being more sensitive to shape errors versus 1.52 λ/D for SRM. By allocating this reserve to account for the HabEx sensitivity, it allows the S5 KPPs to be applicable for both SRM and HabEx. Additionally, because of the size difference of the rendezvous starshade versus HabEx, a full scale prototype assembly for Starshade Rendezvous would be approximately half scale for HabEx (3/8 scale for petal length and ½ scale for disk diameter). Given how well the scaling relationship is known for the mechanical structure, it can be concluded that the planned S5 test articles will fully advance the HabEx starshade to TRL5.

PROGRESS TO DATE:

By design, the S5 development plan is split into two phases. The early phase, which extends into spring 2020, is designed to achieve the TRL5 designation for formation flying and starlight suppression including scattered sunlight and TRL 4 for mechanical technologies. Since the start of the S5 activity, the team has achieved all planned Milestones on schedule and is on track to meet the remaining early phase milestones. Most notably, the Formation Flying lateral sensing technology has reached TRL 5 with the achievement of Milestone 4. The progress to date is described briefly here and a more detailed progress report will be provided by NASA/APD to the Decadal Committee later in the fall.

Formation Flying (Milestone 4 completed): The purpose of formation flying and lateral control is to ensure that starlight does not leak into the telescope aperture and overwhelm the faint exoplanet signal. The shadow cast by the starshade has a finite extent, so the telescope and the starshade must fly in formation such that their relative position is maintained to the accuracy required to perform exoplanet science. The technology required to achieve this capability is a validated technique for sensing lateral displacements of the starshade in the telescope pupil, detected as the Poisson spot in out of band starlight. The S5 team used the Starshade Lateral Alignment Testbed (SLATE) to validate a sensor model by demonstrating lateral offset position sensing accuracy to a flight equivalent of ±30 cm (3-sigma) and then using a control system simulation using the testbed validated sensor model to demonstrate on-orbit lateral position control to within ± 1 m (3-sigma).

The sensor scheme is based on imaging of the residual starlight outside the science band diffracted by the starshade using a pupil imager. The sensor uses an “image library” matching algorithm to determine the lateral displacement of the starshade. The image matching approach was validated in a laboratory experiment, finding good agreement with numerical simulation and modeling. The analytic and numerical simulations predicted flight sensor performance better than the requirement of ±30 cm, achieving a precision of < 10 cm for stars *at least ten times fainter* than any target stars. Control was demonstrated using a high-fidelity formation flying Monte Carlo simulation which showed that the proposed lateral offset sensor is adequate for controlling the lateral position of a starshade with respect to a telescope within a 1m-radius. This was achieved across all varied parameters, in stressing operational conditions, and even with the conservative sensor performance assumed. It was also shown that thruster firings are only required every 10-15 minutes, thus providing high observational efficiency for starshade science

The complete results from the Milestone #4 are documented in the Milestone Report (Ref 7) which can be found at the S5 web page. The final report was reviewed by the ExoTAC and they agreed that the milestone was met. With the achievement of Milestone #4, the Formation Flying/Lateral Sensing technology reached TRL5 and the technology gap was closed.

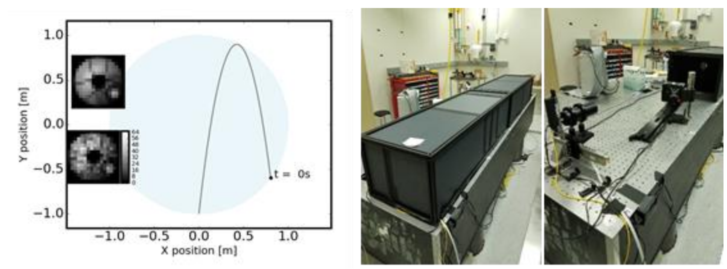

Figure 4 – Formation Flying lateral sensing image matching (left) and Starshade Lateral Alignment Testbed (right)

Starlight Suppression (Milestones 1A, 1B completed; Milestone 2 in progress): The ability of a starshade to suppress starlight and form a dark shadow at 10^{-10} contrast depends on its shape. Milestones 1A, 1B are designed to demonstrate that the correct shape can be designed to achieve 10^{-10} instrument contrast. This is done at a significantly reduced scale of starshade diameter (~1 inch) due to the practicalities of the separation distances required. Testing was completed in the Princeton Starshade Testbed at a single wavelength for Milestone 1A and at multiple wavelengths spanning a 10% broadband for Milestone 1B. The final reports for Milestone 1A and 1B detail the experiment, calibration and the complex results of the experiments (Ref 8, 9). Milestone 1A was the first demonstration at a single wavelength with the average contrast at the IWA of 1.15×10^{-10} with a floor measurement of 2×10^{-11}. Milestone1B was a demonstration of the desired contrast at four wavelengths spanning 640 - 725 nm. At the longest wavelength, on average 15% of the IWA has a contrast better than 10^{-10} the average contrast at the IWA is 2×10^{-10}. The ExoTAC having reviewed the final reports for 1A and 1B agreed that the milestones had been sufficiently met. The successful completion of milestones 1A and 1B have shown that the diffraction equations correctly describe the propagation of light between the starshade and the telescope, leading to the formation of a deep shadow at a contrast level of 10^{-10}.

One limiting effect seen at the laboratory scale of the 1A and 1B experiments is due to the starshade petal gaps being only a few times wider than the wavelength of light. Vector diffraction equations are required to determine the resulting polarization-dependent complex amplitude of the light propagating through the gaps. At the flight scale, the vector propagation amplitudes are expected to be thousands of times smaller than in the laboratory. Thus the detrimental physics encountered in the experiment is not expected to be present at significant levels at the flight scales. Discussions are ongoing now with the ExoTAC as to what additional experiments and measurements can be made in augmentation to the original plan to further validate these scaling effects.

TRL5 will not be reached for optical performance until Milestone 2 is completed. Milestone 2 will validate the model used to predict optical performance by testing a series of subscale starshade masks in the Princeton testbed. These masks will have intentional flaws that will be used to compare test data to model predictions of the contrast due to the flaw. The experimental set of masks for Milestone 2 are in fabrication.

Scattered Sunlight (Milestone 3 in progress): The precision optical edges around the perimeter of the petals must minimize the amount of scattered sunlight reflecting back to the telescope. This scattered sunlight appears as two bright lobes close to the IWA of the starshade. The technical baseline design is an etched amorphous metal edge which showed acceptable scatter results in earlier TDEM testing. To meet Milestone 3, optical edge segments have been fabricated and the scatter performance measured before and after exposure to stressing environments. Testing is complete and results are promising. The report is being written at this time and is on track to be submitted to the ExoTAC for review by the scheduled date of 11/1/2019.

Mechanical Accuracy and Stability (Milestones 5A,6A,7A,7C,8A in progress): A series of five milestones for mechanical performance are in progress due for completion by December 2019. These activities are specifically designed to address the mechanical performance in an incremental fashion. Early testing of assemblies and subsystems with shape/deployment critical features will allow model correlation and refinement. All hardware elements and test campaigns are underway at JPL or its industry partners. Early results are indicating as expected performance.

EVOLUTION AND COMMUNITY INVOLVEMENT

APD/ExEP recognizes that robust and impactful technology maturation requires ongoing consideration of new technology approaches and new mission concept drivers. Therefore, S5 includes activities specifically focused on partnerships and engagement with the science community in order to continually consider new ideas and have opportunities for new participants. These specific activities are collectively called the Starshade Science and Industry Partnership (SIP). The intent of the SIP is to keep an open exchange with the science, academia, government and industry communities to maximize NASA's investment in the technology readiness level of starshades and to keep the technology development activity aligned with the potential future exoplanet science missions as they evolve. The Starshade SIP is open to any organization or individual with research, technology, or science capabilities and contributions in starshade-related technology. Non-US participation is also welcome. As outlined in the SIP charter, expected benefits include:

- Solutions to challenges faced by the S5 development activity;
- New approaches, techniques, and research beyond planned S5 activities that can maximize starshade technology readiness;
- New mission concept drivers for starshade technology performance requirements;
- Alignment between S5 technology development activities and future mission needs;
- Facilitate groups of investigators to communicate research, new technology, and new mission concepts across disciplinary, organizational, and geographic boundaries;
- Continued participation of the community in NASA's starshade technology development.

Specific elements of the SIP include NASA's appointment of a Technology and Science Working Group (TSWG) to act as a Steering Committee for this community input, small business subcontracts for novel yet relevant contributions to the technology development, bi-annual face to face forums for the community to meet and discuss topics of interest, regular (bi-monthly) telecons to share progress and details about the on-going S5 technology development activities. As of the writing of this white paper, the SIP activities are well underway. The TSWG has been selected and appointed by NASA/APD to facilitate the community participation and synthesize the input to S5/ExEP. Four small business contracts have been awarded. Five telecons have been held in which progress on S5 Milestones were presented to the community participants. The first face to face forum is being planned for early Fall 2019. Because the SIP is intended to provide and collect information from the broader starshade community, all information, is available on the S5 webpage.

Two assessment reviews are planned in the S5 baseline schedule to allow NASA/APD the opportunity to redirect S5 plans to respond to emerging needs, discoveries or external developments. Technical or programmatic changes can be considered at these reviews to make course corrections or adjustments in future S5 plans to maximize the value of the technology development activity.

CONCLUSION

Starshades are one of several important techniques for achieving the goals of exoplanet detection and characterization. With the focused investments by NASA in starshade technology, the potential for infusion into flight missions is within reach. NASA's Starshade Technology to TRL 5 (S5) activity is designed to be synergistic and supportive of the mission concepts being considered now and in the future. The scope of the activity as captured in the Technology Milestones defines the technical performance, fidelity and environments consistent with the identified needs of multiple mission concepts. The S5 activity builds on the success of the previous TDEM investments and is making progress on achieving its defined milestones. The activity is open to the community to provide feedback and contributions above and beyond what is in the baseline plan. The reader is encouraged to dive deeper into the information that is publically available on the S5 web page (https://exoplanets.nasa.gov/exep/technology/starshade/). In addition, a more comprehensive technical progress report will be delivered directly to the Decadal Committee by NASA along with the mission concept study reports.

REFERENCES

1. NASA Procedural Requirements NPR7123.1B, effective date April 18, 2013.
2. NASA Strategic Plan 2014
3. "Starshade to TRL 5 (S5) Technology Development Plan", Document Owner: Dr. Phil Willems, September 13, 2018.
4. Starshade TRL-5 Preliminary Development Plan Authorization Memo", NASA Astrophysics Division Director.
5. Exoplanet Exploration Program 2018 Technology Plan Appendix, section C.
6. "Starshade to Technology Readiness Level 5 (S5) Technology Development Plan (TDP) Decision Memo", NASA Astrophysics Division Program Management Panel.
7. "S5: Starshade Technology to TRL5 Milestone 4 Final Report: Lateral Formation Sensing and Control", Thibault Flinois, Michael Bottom, Stefan Martin, Daniel Scharf, Megan C. Davis, Stuart Shaklan, Jet Propulsion Laboratory, California Institute of Technology, 14 Nov 2018
8. "Starshade Technology Development Activity Milestone 1A: Demonstration of High Contrast in Monochromatic Light at a Flight-like Fresnel Number", Anthony Harness, N. Jeremy Kasdin, Michael Galvin, Princeton University, Stuart Shaklan, Kunjithapatham Balasubramanian, Victor White, Karl Yee, Richard Muller, Philip Dumont, Simon Vuong, Phillip Willems, Jet Propulsion Laboratory. January 28 2019.
9. "Starshade Technology Development Activity Milestone 1B: Demonstration of High Contrast in Broadband Light at a Flight-like Fresnel Number", Anthony Harness, N. Jeremy Kasdin, Michael Galvin, Princeton University. Stuart Shaklan, Kunjithapatham Balasubramanian, Victor White, Karl Yee, Richard Muller, Philip Dumont, Simon Vuong, Phillip Willems Jet Propulsion Laboratory, California Institute of Technology, March 28, 2019.
10. Starshade Rendezvous Probe Report, Feb 2019.
11. HabEx Final Report, expected August 2019.