Starshade to TRL5 (S5) Technology Development Plan

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1 INTRODUCTION

The 2014 NASA Strategic Plan has as its first Strategic Goal to "expand the frontiers of knowledge, capability, and opportunity in space", with the accompanying Strategic Objective 1.6, "discover how the universe works, explore how it began and evolved, and search for life on planets around other stars."[1] In accordance with these goals and objectives, NASA's Astrophysics Division has implemented the Exoplanet Exploration Program for the aims of "discovering planets around other stars, characterizing their properties, and identifying candidates that could harbor life."[2] 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)."[3]

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.

The Exoplanet Exploration Program (ExEP) plan states that 'the Program supports precursor ground science and technology activities necessary to enable future exoplanet space mission objectives."[4] To that end, the ExEP has funded community work on starshade technologies, via competed grants within the Program's Technology Development for Exoplanet Missions (TDEM) funding line, with the goal to mature these technologies to the point at which starshades could be integrated into potential future exoplanet detection and characterization missions. The ExEP also manages facilities critical for the execution of starshade technology development activities, at JPL and in coordination with relevant institutional authorities outside of JPL. 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).[5] This focused activity is called S5. This document contains the Technology Development Plan (TDP) for S5.

[1] *2014 NASA Strategic Plan, p. iii and p. 21.*
[2] *2014 NASA Science Plan, p. 77, and Exoplanet Exploration Program Charter, section 1.*
[3] *Exoplanet Exploration Program Charter, section 4.4*
[4] *Exoplanet Exploration Program Plan, Revision A, p.8.*
[5] *Memo by Paul Hertz dated March 23, 2016.*

1.1 PURPOSE AND SCOPE

The purpose of the S5 Technology Plan is to document the development roadmap chosen to mature the technology readiness level (TRL) of Starshade technology to TRL5.

The scope of this Plan encompasses the technology development objectives, key performance parameters (KPPs), detailed activities, management approach, and cost, schedule, and workforce requirements. In addition to background material on starshade technology and the Starshade Rendezvous mission concept, this Plan includes:

- A description of the content and flow of the work;
- Assumptions as to funding, personnel, facilities, and other applicable resources;
- Plans for industry involvement and partnerships;
- A Work Breakdown Structure (WBS);
- A master schedule per the WBS;
- Cost and workforce requirements per the WBS;
- Milestones and deliverables per the WBS;
- A management plan that defines a management approach and organization, plans for reviews and reporting, a risk management process.

1.2 STARSHADE MISSION CONCEPTS AND CONTEXT

1.2.1 *NASA'S NEED FOR 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.

Most exoplanets have been discovered and studied by methods that carefully study light from the exoplanet's host star, and not from the exoplanet itself. The radial velocity method determines the mass and orbital parameters of the exoplanets by measuring the reflex motion of the star under the (unseen) exoplanet's gravitational pull. The astrometric technique gets the same parameters by measuring the varying position of the star with respect to other stars to infer the reflex motion. The radial velocity method has been widely and successfully used in exoplanet study for decades; astrometry has been far less successful to date, although the European Space Agency's GAIA mission is expected to change this. The transit method studies exoplanets by measuring the attenuation of starlight as the exoplanet passes between its host star and Earth. This method determines exoplanet sizes and orbits, and can in some situations reveal information about exoplanet masses (through transit time variations induced by gravitational interactions with seen or unseen exoplanetary companions) or atmospheres (through careful study of minute changes in the observed stellar spectrum as a small part of the starlight passes through the exoplanet atmosphere). The gravitational microlensing method measures photometric changes not of the exoplanet host star, but of a distant background field star, as the exoplanetary system passes in front of it. This method mainly measures exoplanet masses and separations, which provide limited information about orbital parameters.

Direct imaging can provide detailed information about exoplanet surfaces and atmospheres by measuring the spectrum of light emitted or reflected from the exoplanet, independently of the host star. For most exoplanets, the characterization of habitability (presence of constituents like water or oxygen, for example), can only be done through direct imaging. The transit technique is generally not sensitive enough to constrain atmospheres of small, rocky planets orbiting Sun-like stars, and can say nothing about the majority of exoplanets that do not transit their host stars.

Direct imaging of an exoplanet requires that the light from its host star be greatly suppressed at very small angular separations. Astronomers have developed coronagraphs and starshades to this end for many years. Coronagraphs have had a significant head start; the first coronagraph was built by Lyot to study the solar corona in 1931.[6] Since then many styles of coronagraph have been introduced to occult either resolved objects like the Sun or unresolved objects like stars, and many have been employed on both ground- and space-based telescopes, including the Hubble Space Telescope. Coronagraph development continues to this day. WFIRST includes a coronagraph instrument (CGI) as a technology demonstration in its baseline design. The CGI will push coronagraphic high-contrast technology toward a level that can image small rocky worlds in habitable zones.

Building a coronagraph capable of this performance is technically challenging. High-performance coronagraphs employ masks and/or phase plates in the image and/or pupil planes to distinguish the exoplanet light from the starlight with very high fidelity. Mirror distortions and scattered light must be controlled at a high level, including by wavefront control actuators. Obscured apertures (like that in WFIRST) lead to difficult design features in the masks and phase plates and their alignment.

Starshades represent a separate approach to the problem. Rather than separate the starlight from the exoplanet light within the telescope, the starshade's purpose is to prevent the starlight from entering the telescope at all. Doing this allows many simplifications of the telescope and camera optics. The amplitude and phase masks are no longer necessary to the exoplanet imaging, larger mirror distortions are tolerable (thus wavefront control is no longer necessary), and obscured or segmented apertures present no particular problem. The costs of these benefits are: the need for a separate spacecraft; the added complexity of formation flying; the complexity of deploying and holding the large starshade to precise tolerances; control of stray sunlight from the starshade; and the need for lengthy repositioning maneuvers of the starshade form target to target, which drive the quantity of propellant.

NASA will need to continue to advance both coronagraph and starshade technologies to further its mission to search for life on distant planets. The objective of this Plan is to develop starshade technology to TRL5.

[6] *B. Lyot, 'Photography of the solar corona outside eclipses", Comptes Rendus Hebdomadaires des Seances de L'Academie des Sciences vol. 193 pp. 1169-72 (1931).*

1.2.2 *PREVIOUS AND ONGOING MISSION STUDIES AND WORKING GROUPS*

Several starshade mission concepts have been studied; new concepts continue to be proposed. The New Worlds imager concept study was conducted under a NIAC grant in 2005-8;[7] among the missions considered were a starshade flying in formation with the James Webb Space Telescope,[8] and one or more starshades flying in formation with a dedicated 4-m telescope. Following on the work of the concept study, the New Worlds Observer mission concept study was submitted to the 2010 Decadal Survey.[10] This mission concept involved a 50-m diameter starshade flying in formation with a 4-m aperture telescope. Also at this time, the Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy (THEIA) mission concept was submitted to the 2010 Decadal Survey.[11] This flagship mission concept involved a 40-m diameter starshade flying in formation with a 4-m aperture telescope.[12] At the time, the formation flying required for the mission concept was considered to be enormously challenging, and the cost ($5B) and technical maturity of a 4-m aperture space telescope to be underestimated.[13] The Occulting Ozone Observatory, a probe-class mission concept pairing a 34-m starshade with a 2-m aperture telescope, was also considered at this time.[14]

In 2013-2015 the Exo-S Science and Technology Definition Team (STDT) was charged by NASA to demonstrate a viable starshade-telescope space mission with a $1B cost cap (probe class). The Exo-S final report,[15] along with its later update,[16] considered two basic types of design reference mission: a Dedicated mission, in which a 30-m starshade and a 1.1-m aperture telescope launch together on the same rocket, and a Rendezvous mission, in which a 34-m starshade launches separately to rendezvous with a 2.4-m aperture telescope that has already begun its operations (i.e., WFIRST). Several flavors of both basic missions were studied, covering a range of mission costs and science objectives. One of them, called the Rendezvous Case Study mission, formed the basis for a probe study currently underway, called Starshade Rendezvous.

In November 2015, the NASA ApD chartered the Habitable Exoplanets (HabEx) large mission study, like THEIA a flagship mission concept.[17] In January 2016, the ExEP chartered the Starshade Readiness Working Group (SSWG) to recommend to the ApD Director a path to TRL6 for starshade technology. Among the findings of the SSWG was that a ground-based technology development strategy exists to enable a Starshade/WFIRST Rendezvous by launch readiness date

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[7] *W. Cash et al., New Worlds Imager Final Report to the NASA Institute for Advanced Concepts, 2005.*

[8] *W. Cash et al., "The New Worlds Observer: using occulters to directly observe planets", Proc. SPIE 6265, 62651V-1 (2006).*

[10] *"The New Worlds Observer" White Paper submitted to the NRC ASTRO-2010 Survey, W. Cash; W. Cash et al., "The New Worlds Observer: the astrophysics strategic mission concept study", Proc. SPIE 7436, 743606-1 (2009).*

[11] *Note that the name THEIA has been adopted for a new, unrelated astrometric mission concept by the ESA.*

[12] *"THEIA: Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy" White Paper submitted to the NRC ASTRO-2010 Survey, N. J. Kasdin.*

[13] *"The THEIA Study", N.J. Kasdin, presentation to the HabEx Face-to-Face meeting, May 17, 2016.*

[14] *D. Savransky et al., "Occulting Ozone Observatory Science Overview", Proc. SPIE 7731, 77312H-1 (2010).*

[15] *Exo-S Starshade Probe-Class Exoplanet Direct Imaging Mission Concept Final Report, March 2015.*

[16] *"Exo-S Probe Study Update", Exoplanet Exploration Program Office, November 22, 2017.*

[17] *HabEx interim report.*

FY26-28, and that this development was likely to provide significant technology benefits to HabEx.[18]

The ExEP 2018 Technology Plan Appendix lists five technologies within three technology gaps that must be advanced in order bring the starshade to TRL5.[19] These gaps are in the areas of starlight suppression, mechanical shape stability and deployment accuracy, and formation flying between the starshade and telescope. Section 1.2.4 of this document describes these gaps in fuller detail. The goal of S5 is to bring a system with all these technologies to TRL5.

The technical readiness level of a technology cannot be evaluated independently of the mission in which it will be used. This TDP takes as its working assumption that the Starshade Rendezvous Mission (SRM) would be the first starshade mission. The Key Performance Parameters (KPPs) the starshade must meet to reach TRL5 flow down from the Starshade Rendezvous mission concept study. The starshade KPPs for the HabEx mission are, as of this writing, identical to those for Starshade Rendezvous. 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. Thus a high fidelity, full scale prototype assembly for Starshade Rendezvous would be of less than full scale and therefore of lower fidelity for HabEx. The S5 technology development plan defines TRL5 test article fidelity for Starshade Rendezvous only. While some of the technology needs for the smaller WFIRST rendezvous concept are directly applicable to a larger starshade, some may require different solutions. NASA has commissioned another flagship mission concept study that would directly image exoplanets, known as LUVOIR.[20] Currently the LUVOIR mission does not include a starshade in its baseline architecture; instead, a coronagraph meets its starlight suppression needs. It does consider a starshade as a potential mission enhancement. The flagship requirements on starshade technology may change in the coming years as the HabEx and LUVOIR STDTs further advance their mission concepts.

Although this Plan assumes 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 ~2.4m aperture operating in an Earth-Sun L2 orbit, so long as it includes a pupil plane sensor consistent with the lateral position sensing concept.

The key beneficiaries for this technology are: the Starshade Rendezvous probe study and the HabEx flagship study, both of which rely on starshades to implement their missions; the LUVOIR flagship study, which considers a potential starshade enhancement; and the Decadal Survey, which needs well-developed starshade technology to be able to recommend missions that employ starshades. Some personnel implementing S5 also participate in the Starshade Rendezvous and HabEx studies, and non-S5 personnel from SRM and HabEx will be invited to S5 reviews to ensure that the S5 technology development remains aligned to their needs. The WFIRST mission has a requirement to be Starshade compatible- S5 personnel work with the WFIRST team to compose a

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[18] *"Starshade Readiness Working Group Recommendation to Astrophysics Division Director", G. Blackwood, S. Seager, N. Siegler, and T. Hyde, November 9, 2016, page 5.*

[19] *Exoplanet Exploration Program 2018 Technology Plan Appendix, section C.*

[20] *LUVOIR interim report.*

WFIRST/Starshade Interface Requirements Document that outlines what is required for compatibility.

1.2.3 *KEY SCIENCE PERFORMANCE REQUIREMENTS*

The key science performance requirements from the Starshade Rendezvous probe study are as follows.

<u>Inner Working Angle</u>: The inner working angle is the minimum angular separation between an exoplanet and its host star, such that the exoplanet is visible outside the starshade. Ideally, the inner working angle should be as small as possible, to reveal as much of the exoplanetary system as possible.

<u>Suppression/Contrast of Light from the Host Star</u>: This is the degree to which the host starlight is blocked by the starshade at the telescope, with suppression referring to the overall light reduction at the telescope's pupil plane and contrast referring to the light reduction at the telescope's image plane, at the exoplanet location. Ideally, this too should be as low as possible. In practice, suppression of starlight beyond a certain level does not improve the science yield of a starshade mission because resolved foreground light from zodiacal dust and resolved background light from exozodiacal dust then dominates. The key science performance requirement is chosen to reduce starlight to be smaller than these noise sources.

<u>Stray Light</u>: The starshade, having very little angular separation from the exoplanet, must not emit or scatter stray light (for example, from the Sun) into the telescope at a level that impairs exoplanet imaging performance. Again, less scattered light is always better, but reducing the stray light below the limit imposed by resolved foreground and background light does little to improve the mission science yield.

<u>Environment</u>: The Starshade will operate in an L2 orbit.

<u>Formation Flying</u>: Integration times for exoplanet imaging will last from hours to days. The starshade must be capable of maintaining its position between WFIRST and the target star for these durations. In addition, the starshade must be able to reposition itself from one target star to the next.

<u>Mission Duration</u>: the Starshade Rendezvous mission assumes 2 years prime mission duration.

The starshade S5 Key Performance Parameters (KPPs) flow down from these key science performance requirements. We summarize those KPPs in Section 1.3.1 and in Table 1: the flow down rationales are given in the individual technology sections 2.1-2.3 below.

1.2.4 *KEY TECHNOLOGY GAPS*

Starshades suppress on-axis starlight to enable the direct imaging of exoplanets. It does this by blocking the on-axis starlight 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. 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, 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. Independent optical modeling predictions have shown excellent agreement with one another concerning the contrast sensitivity to petal shape errors[21], and detailed preliminary error budgets have been proposed.[22]

The starshade scientific community assigns specific meanings to the terms 'contrast' and 'suppression'. '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. "Suppression' refers to the ratio of total starlight that enters the telescope with the starshade in place, to the power that enters without the starshade, and is measured in the telescope pupil plane. Suppression is a property of the starshade alone; contrast is a property of both the starshade and the observatory.

As mentioned above, the ExEP Technology Plan Appendix lists three technology gaps for a starshade, with five separate technologies that require development to close the gaps. (See Figure 1.) These gaps are:

1. **Starlight Suppression** – the optical characteristics the starshade must have to reduce light not from the exoplanet to levels low enough for exoplanet detection. The knowledge of which starshade shapes will suppress the exoplanet host star's light at the 10^{-10} level is currently based on optical models that lack high fidelity 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 one technology within this gap, and is labeled S-2 in the ExEP Technology Plan Appendix. The other major unwanted noise from the starshade is from sunlight scattered off its edges. Edges that limit scattered sunlight to acceptable levels is the other technology within this gap, labeled S-1.
2. **Formation Sensing and Control** – the ability to sense and control the lateral offset between the starshade and the telescope maintaining 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. This technology is labeled S-3.
3. **Deployment Accuracy and Shape Stability** – the ability to manufacture, stow, launch, and deploy the starshade with a shape within the deployment tolerances budgeted to meet the contrast requirements. The final shape must be stable throughout operational environments within an allocated error budget. The optical shields within both the petals and the inner disk must fully deploy as an opaque structure. Within this technology gap are two separate

[21] *Shaklan, S. B., Noecker, M. C., Glassman, T., et al., "Error budgeting and tolerancing of starshades for exoplanet detection," Proc. SPIE 7731, 77312G (2010).*
[22] *Shaklan, S. B., Marchen, L., Lisman, P. D., et al., "A starshade petal error budget for exoearth detection and characterization," Proc. SPIE 8151, 815113, (2011).*

technologies, a) precision fabrication of stable petal shapes (S-4), and b) reliable deployment of the starshade to bring the petals stably to their precise positions (S-5, not to be confused with the activity name S5).

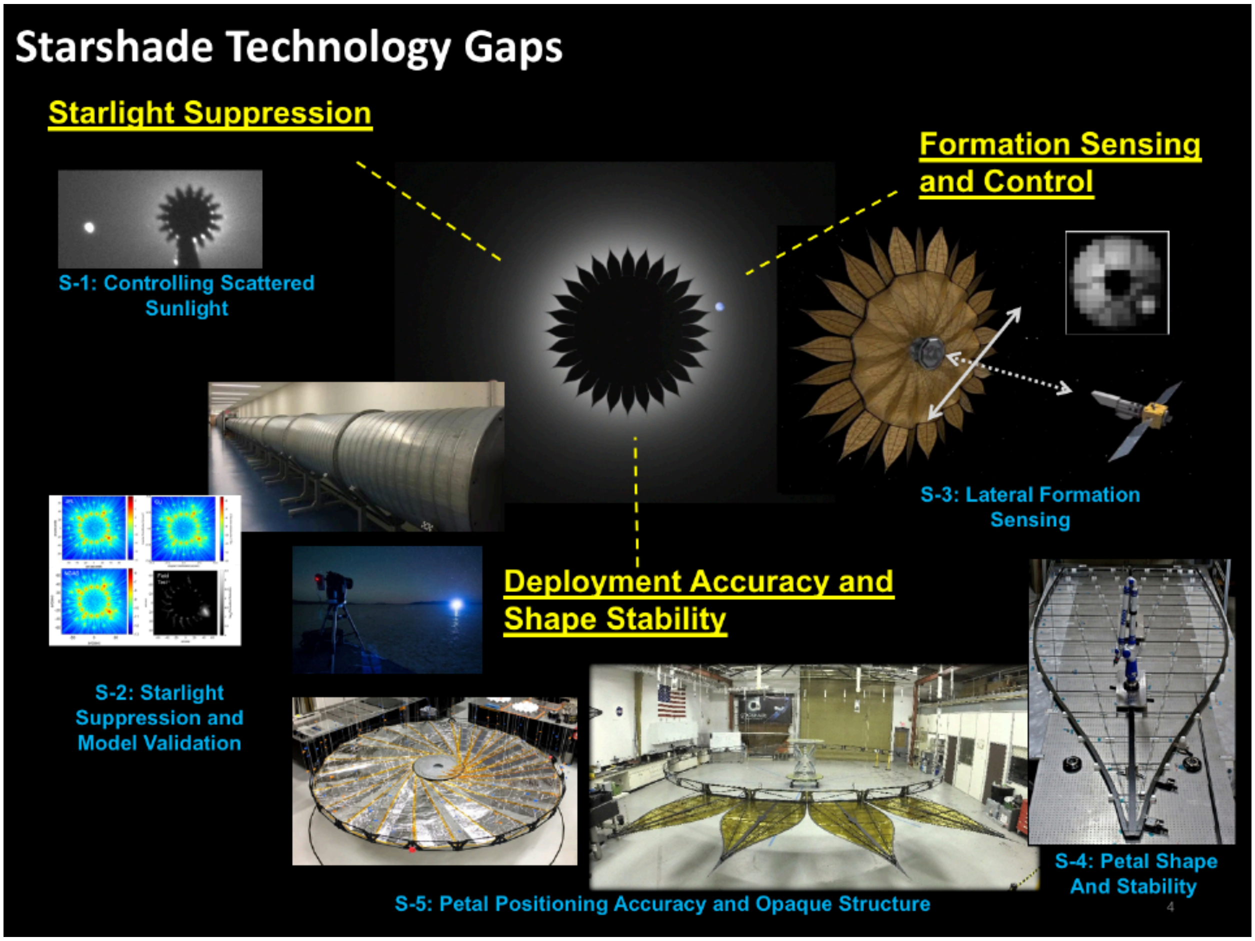

Figure 1: Starshade technologies and technology gaps.

1.2.5 *KEY TRADES*

In the work that predates this Technology Development Plan, several key trades were investigated. We briefly introduce them here. Further elaboration, when needed, will be given in the relevant subsections of Section 2.

1.2.5.1 **Folded vs. Wrapped Architecture**

The baseline starshade mechanical architecture described in Section 2.3.1 uses flexible petals mounted around an Astromesh perimeter truss. This design can be stowed into the fairing of a launch vehicle by collapsing the truss into a tight cylinder, and then wrapping the petals around this cylinder. S5 also considered a second mechanical architecture, spearheaded by Northrop-Grumman. In this design the petals and central obscuration are more integrated, and are folded along several planes into a volume that can be stowed in a launch fairing, to then be deployed using telescoping booms similar to those used in the James Webb Space Telescope.[23] S5 chartered a Trade Evaluation Team (TET) to evaluate both designs and issue findings to the ExEP[24] that then informed a downselect by NASA's Astrophysics Division Director.[25] The Director's decision baselined the wrapped architecture now used by S5.

1.2.5.2 **Blunt vs. Sharp Optical Edges**

Numerous materials, shapes, treatments, and optical models have been considered for the optical edge.[26] Coupons for many of the most promising materials were manufactured and tested in scatterometers to determine which best met the solar glint requirements for starshades. The data are shown in Figure 8 of Section 2.1.7. Based on these tests, etched amorphous metal was chosen for S5 as the only option to date that meets requirements.

1.2.5.3 **'Putting' vs. Linear Formation Flying Acquisition**

For much of the targeting or retargeting maneuver of a starshade, both the starshade and the exoplanet host star are visible to the telescope. During the final few tens of meters of the maneuver, the starshade starts to diffract light from the host star, which complicates the final acquisition. Early concepts of operations ('conops') for starshade considered a linear formation flying acquisition, in which features in the periphery of the starshade shadow would be measured and used to guide the starshade.[27] More recent work showed that it is simpler and no less robust or efficient for the starshade to coast across the partial alignment region into the center, a 'golf putt' maneuver.[28] Putting has now been baselined into the starshade formation flying conops (see Section 2.2.1). The technology for putting is considered already to be at TRL5 and no activities are envisioned relating to it in this plan.

1.2.5.4 **Choice of Apodization Function**

The early insights that showed that starshades could realistically be built with starlight suppression adequate for exoplanet imaging considered starshade apodization profiles with simple analytical expressions, such as the hypergaussian design family.[29] Hypergaussian designs have the desirable feature of suppression stopbands extending deep into blue wavelengths. However, retaining this advantage while meeting performance requirements requires very long and narrow petal tips that would be difficult to keep straight. The baseline optical shape uses a more complex shape determined by algorithms to satisfy chosen criteria. These criteria allowed the loss of suppression at blue wavelengths and also permitted wider petal tips for ease of manufacture. The blue-end starlight

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[23] T. Glassman et al., "Starshade starlight-suppression performance with a deployable structure", Proc SPIE vol. 9904, art. no. 25 (2016).

[24] G. Blackwood, "Starshade Mechanical Architecture Trade" recommendation to ApD Director, May 16, 2018.

[25] Hertz decision documented in email to ExEPO.

[26] S. Martin et al., "Starshade optical edge modeling, requirements, and laboratory tests", Proc. SPIE vol. 8864, art. no. 1A (2013); S. Casement et al., "Results of edge scatter testing for a starshade mission", Proc. SPIE vol. 9904, art. no 3H (2016).

[27] D. Scharf et al., "Precision formation flying at megameter separations for exoplanet characterization", Acta Astronautica vol. 123, pp. 420-34 (2016).

[28] M. Bottom et al., "Precise starshade stationkeeping and pointing with a Zernike wavefront sensor", Proc. SPIE vol. 10400, art. no. 1B (2017).

[29] W. Cash, "Detection of Earth-like planets around nearby stars using a petal-shaped occulter", Nature vol. 442 pp. 51-3 (2006).

leakage can be beneficial, allowing operation with science wavelengths redder than the lateral alignment sensing wavelengths. The method of starshade shape determination is described in Section 2.1.3.

1.3 GOALS AND OBJECTIVES OF THIS TECHNOLOGY DEVELOPMENT PLAN

1.3.1 *KEY PERFORMANCE PARAMETERS*

The Key Performance Parameters to be met by a starshade for a Rendezvous mission with WFIRST are summarized in Table 1. All key performance parameters derive ultimately from the contrast requirement for observing and characterizing Earthlike exoplanets. As seen from a nearby star, the Earth at quarter phase is 1×10^{-10} times as bright as the Sun; this sets the rough contrast goal for direct imaging of exoEarths. For an exoplanet that is observed against a dark background, better contrast will reduce the residual starlight below that of the exoplanet, and reduce integration times needed to get a given signal to noise ratio. However, resolved zodiacal and exozodiacal light around the exoplanet sets a practical limit to how much the integration time can be reduced by improving starshade contrast. The Exo-S Design Reference Mission for the Starshade Rendezvous assumes a combined zodi-exozodi surface brightness of 7 times the nominal local zodi level,[30] or 20.9 mag/arcsec^2. With this background, an instrument contrast of 1×10^{-10} in the Starshade Rendezvous mission increases the background counts and the integration time by ~15% for a V=5 star and 37% for a V=4 star. For brighter stars, the instrument background is still more important, but integration times become so short that overall impact on their DRM is minimal. This photometric analysis drives a requirement that the starshade contrast be better than 1×10^{-10}. This directly drives the Starlight Suppression KPP requirement for contrast better than 1×10^{-10}.

Table 1: Summary of Key Performance Parameters. Details of the specifications are given in Section 2 of this document.

Technology Gaps	KPP #	KPP Specifications	KPP Threshold Values	Threshold Contrast	KPP Goals
Starlight Suppression	1	Demonstrate flight **instrument contrast** performance at inner working angle is viable via small-scale lab tests	1×10^{-10}	N/A	5×10^{-11}
	2	Validate **contrast model accuracy** relative to flight-like shape errors	≤ 25%	N/A	≤ 10%
Solar Scatter	3	Verify **solar scatter** lobe brightness visual magnitude	V ≥ 25 mags	N/A	V ≥ 26 mags
Lateral Formation Sensing & Control	4	Verify lateral **position sensor accuracy** and that it supports ± 1 m control via simulation	≤ ± 30 cm	1×10^{-11}	≤ ± 10 cm
Petal Shape	5	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	≤ ± 70 µm	1×10^{-11}	≤ ± 50 µm
	6	Verify on-orbit **thermal shape stability**	≤ ± 80 µm	8×10^{-12}	≤ ± 40 µm
Petal Position	7	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	≤ ± 300 µm	1×10^{-12}	≤ ± 212 µm
	8	Verify on-orbit **thermal shape stability**	≤ ± 200 µm	1×10^{-12}	≤ ± 100 µm

The Exo-S study also identifies a systematic noise floor, separate from the photometric noise floor. Where the photometric noise floor describes a relatively uniform haze of light around the starshade that

[30] *Exo-S Final Report, page 6-22.*

blends with the exoplanet signal, the systematic noise floor describes 'structures' in that haze of light that could be mistaken for exoplanets themselves. The Lateral Position Sensing KPP then flows down from the contrast requirement, in that the contrast degrades as the starshade moves away from the telescope/star axis. The Exo-S DRMs required the systematic background be no greater than the 4 x 10^{-11} contrast expected for an exoEarth, and that it be characterized to a level 10X better.

The Lateral Position Sensing KPP flows down from the application of this requirement to the formation flying. The starshade will cast a shadow that is ~2 meters wider than the telescope aperture if it is to meet the contrast requirement while minimizing the inner working angle. If the starshade moves laterally by some fraction of this size margin, starlight will leak preferentially around the inward edge of the starshade and create localized brightness that could be mistaken for an exoplanet. Keeping the starshade within 1 meter of the viewing axis maintains the systematic noise level at $5x10^{-12}$, the desired factor of ~10 below the systematic noise floor necessary for its calibration. The need to measure the starshade lateral position to better than the control requirement then drives the 30cm lateral position sensing KPP.

The Petal Shape and Petal Position KPPs flow down from both the photometric and systematic noise floors. The allowable tolerances in the starshade's fully deployed shape depend on the what type of shape change is considered. For instance, the most critical parameter to contrast performance is the global radial positions of the petals. The 300 micron tolerance KPP for the petal position is based upon the dependence of photometric contrast on this tolerance. On the other hand, individual petal shape departures tend to produce localized bright spots in the image plane, and so are also driven by the systematic noise floor. Section 2.1.4 describes the error budget for the starshade shape that is used to derive these tolerances.

The starshade KPPs described above are driven by the need to suppress the light of the exoplanet's host star relative to that of the exoplanet. This naturally leads to their description in terms of contrast or suppression, since these ratios are nominally independent of the host star's apparent magnitude. The scatter of sunlight from the starshade to the telescope will be highly localized from a few regions where the petal edges are best aligned for direct reflection in that direction, and are seen by the telescope as two point sources; thus scattered sunlight contributes to the systematic noise floor. But the scattered sunlight power at the telescope is independent of the exoplanet host star's apparent magnitude. It therefore is better described by an apparent magnitude than by a contrast ratio. A model used by the Exo-S study showed that these two scatter lobes would increase the integration time by 25% if their magnitude was V=25. The Solar Scatter KPP is chosen on that basis.

Figure 2 depicts how the tolerances for the KPPs have been allocated.

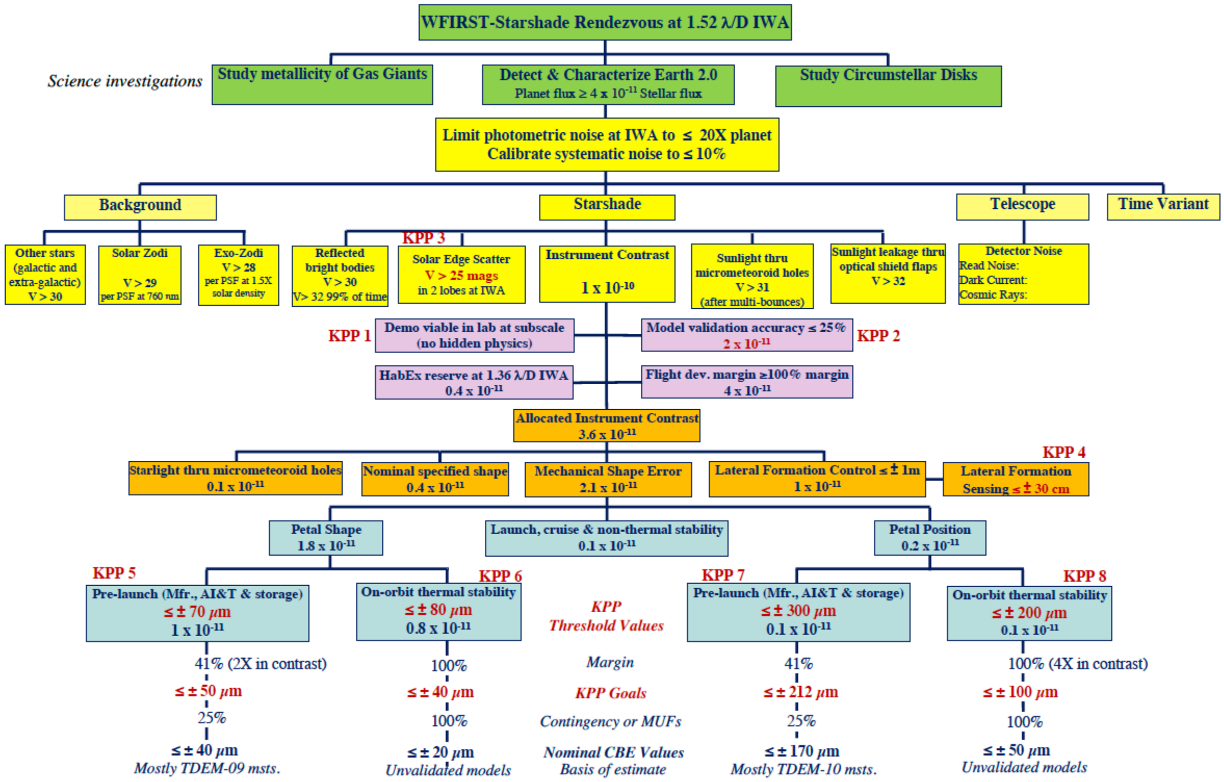

Figure 2: Flow down of Key Science Parameters of Starshade Rendezvous mission to Key Performance Parameters of starshade itself.

1.3.2 *TRL5 DEFINITIONS AND EXIT CRITERIA*

The five technologies that S5 will develop are diverse. We therefore defer the descriptions of the exit criteria for these technologies, and the relevant environments, test article fidelities, analyses, and measurements required to demonstrate them, to Sections 2.1.5, 2.1.7, 2.2.2, 2.3.3, and 2.3.4 below. A high-level summary is provided in Table 9.

1.3.3 *KEY ASSUMPTIONS, NEEDS, AND CHALLENGES*

The S5 technology development activity operates within several programmatic and institutional constraints.

As outlined in the ExEP Technology Plan, the potential future missions with the most mature designs requiring a starshade are Starshade Rendezvous and HabEx. These mission concepts are currently under study. HabEx is one of four flagship mission concepts that NASA is developing for the upcoming Decadal Survey, with the final report to be submitted to the Decadal committee for consideration in July 2019. Starshade Rendezvous is one of ten probe mission concepts chartered by NASA, with final reports due to NASA by December 31, 2018, and submission to the Decadal committee at around the same time as the flagship final reports. The Decadal committee will begin its deliberations in January 2019 and issue its report sometime around December 2020. This technology development plan is therefore organized around the goal of submitting a white paper to the Decadal committee reporting on the TRL5 status of starshade technology by the spring of 2020.

WFIRST is currently in its Preliminary Design Phase (Phase B). The Starshade Rendezvous mission will require WFIRST to be starshade compatible, and starshade compatibility is a baseline technical performance requirement of WFIRST. It is desirable to incorporate these performance capabilities into the WFIRST design as soon as practical, when they can be done least expensively. The only technology gap for starshades that impacts the WFIRST design is the formation sensing and control. The formation sensing and control technology development schedule completes earlier than the other technology gaps compatible with WFIRST needs- the details can be found in Section 2.2.2.

S5 has been instructed to plan to the funding profile shown in Table 2. This level of funding is insufficient to bring all five starshade technologies to TRL5 in time for a report to the Decadal Committee. Assuming additional funding will not be found in FY19-20 to accelerate S5, this technology development plan matures the formation flying technology, the starlight suppression and solar scatter technologies to TRL5 in time for the white paper to the Decadal Committee. Petal shape and deployment technologies, which are the most expensive, are planned to reach TRL5 by 2023. The milestone schedule for these activities is designed to address critical issues leading to TRL5 in time for input to the Decadal Committee.

Table 2: Funding profile for S5 technology development activity.

Starshade HQ NOA Guideline	PRIOR	FY18	FY19	FY20	FY21	FY22	FY23	TOTAL
Redacted								

Starshade technologies have differing export compliance requirements. No starshade technologies are ITAR controlled. All other starshade technologies fall under EAR status. The ITAR/EAR classifications for each technology are elaborated in the relevant technology subsections of Section 2 below.

The S5 plan to reach TRL5 does not include any flight testing, nor is flight testing anticipated for any following work to reach TRL6. This decision was made upon the recommendation of the Starshade Readiness Working Group (SSWG) to NASA's Astrophysics Division in 2016.[31] In making this recommendation, the SSWG reported these findings:

- "A ground-only development strategy exists to enable a starshade science flight mission such as WFIRST Starshade Rendezvous"
- "A prior flight technology demonstration is not required prior to KDP-C of WFIRST Rendezvous"
- "Development solutions exist that support a WFIRST Starshade Rendezvous by LRD FY26-28"
- "Technology development for a Starshade Rendezvous mission is likely to provide significant technology benefits to both the HabEx and LUVOIR large mission studies"
- "Two optional enhancements to the SSWG-recommended development approach recognized:"

[31] *"Starshade Readiness Working Group Recommendation to Astrophysics Division Director", G. Blackwood, S. Seager, N. Siegler, and T. Hyde, November 9, 2016, page 5.*

- "A flight technology demonstration (mDOT) would enhance the ground development strategy for formation flying sensing and control and optical performance with additional cost and technical risk"
- "Long baseline ground demonstrations in air may provide some additional benefit for optical verification but at medium-to-high risk for interpretation of results"

The S5 plan to reach TRL5 is responsive to the strategy outlined by the SSWG in their recommendation, by developing validated models of performance that adequately relate measured ground-based test performance to predicted space-based operational performance that can then be used and further developed if needed during the ground-based TRL6 development activity. The details of this model validation are also given in the individual technology sections in Section 2.0 below.

A key challenge to S5 lies in the demonstration of the starlight suppression KPP using a small-scale mask in an optical testbed. The fabrication of masks small enough to be tested at flight-like Fresnel numbers in a ~100-meter-long test bed, but with fidelity sufficient to meet requirements, is challenging. In addition, the limiting optical physics at this small scale may be significantly different than at full scale. These issues are described more fully in Section 2.1.5 below, and represent the largest risk to the S5 plan, as shown in the S5 risk matrix in Section 3.4.

2 PLAN FOR TECHNOLOGY DEVELOPMENT TO TRL5

2.1 STARLIGHT SUPPRESSION

2.1.1 *FUNDAMENTAL OPTICAL NOISE SOURCES*

The effectiveness of a starshade to directly image exoplanets will be fundamentally limited by astronomical sources of light other than the exoplanet's host star. Exozodiacal dust will surround the exoplanet in some stellar systems; stars and galaxies will be in the background of others. The telescope views the exoplanet and starshade through the diffuse light of zodiacal dust. Suppression of the host starlight will bring all these features into view along with the exoplanet. Background stars and galaxies can be disambiguated from exoplanets through their different proper motions by revisiting the host star at separate epochs.[32] The (resolved) dust will always be present. Suppressing the host starlight to a level significantly below the level set by dust will not result in further reductions of integration time.

We currently have no measurement of exozodi levels around most nearby target stars. For those that have been measured (by either the Keck Interferometer Nuller[33] or the Large Binocular Telescope Interferometer[34]), the typical measurement uncertainty is tens of times greater than the known level around the Sun; however, the distribution of the measurements over these surveys suggests that most stars have exozodi levels not more than a few times the Solar System level. The Starshade Rendezvous probe study assumes that exoplanetary systems have exozodiacal dust at levels equal to

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[32] *The Starshade Rendezvous mission concept includes these revisits, but primarily for orbit determination rather than disambiguation. See also M. Turnbull et al., "The Search for Habitable Worlds. 1: the Viability of a Starshade Mission", Publications of the Astronomical Society of the Pacific 124:418-447 (2012).*

[33] *"Constraining the Exozodiacal Luminosity Function of Main-Sequence Stars: Complete Results from the Keck Nuller Mid-infrared Surveys," B. Mennesson et al., Astrophysical Journal 79:119, 2014.*

[34] *"The HOSTS Survey- Exozodiacal Dust Measurements for 40 Stars", S. Ertel et al., Astronomical Journal 155:194, 2018.*

that in our Solar System. This implies a total dust surface brightness three times that seen in the field due to zodiacal dust alone. (WFIRST will be embedded within the zodiacal dust cloud, and will look out through only half of the dust along any line of sight out of the Solar System, but all the dust both in front of and behind the exoplanet within its planetary system will be seen).

This technology development plan flows down the key science performance requirement on stray light to a requirement that edge scatter not increase integration time by more than 25%, when azimuthally averaged at the inner working angle. For the assumed exozodi level, this is equivalent to a requirement that the stray light not exceed visual magnitude 25. This also sets the requirement on the starlight contrast to 10^{-10} or better.

2.1.2 *STRAY LIGHT SOURCES*

Stray light directed by the starshade toward the telescope from sources other than the exoplanet host star comes from several diverse and potentially significant mechanisms. Scattered sunlight from the starshade edge is the most significant, but first we briefly describe the others and why they do not require technology development. Edge glint is described in Section 2.1.7.

One source of stray light is light emitted by the starshade itself. The starshade will include an LED beacon directed toward the telescope for use during the acquisition phase of formation flying. This light will be at wavelengths outside of the science band, and basic engineering is sufficient to keep it from impacting the science observations. The science bands are in the visible wavelength range and so thermal emission from the starshade also is not important.

Another potential source of stray light is the reflection of light off the surface of the starshade facing the telescope from solar system objects other than the Sun. These would include Earth, other planets, and the Milky Way. An analysis of these reflections[35] has shown that the starshade reflected light at the telescope would be fainter than 30th magnitude for reflected Earthshine as seen at an L2 orbit, so long as the incident angle of the Earthshine at the starshade is greater than about 90 degrees. The starshade must operate outside this angle in any case to prevent sunlight from reflecting directly into the telescope, so reflected Earthshine should pose no problem. The light from other planets and the Milky Way is less than 30th magnitude except over a restricted range of angles, and not worse than 29.6th magnitude even during rare events, e.g. Jupiter aligned directly behind the telescope. On average, the starshade will appear fainter than the background because its reflectivity is less than 100%.

The Sun is 57 magnitudes brighter than a typical candidate exo-Earth, so scatter of sunlight from the vicinity of the starshade is potentially more serious. The Sun cannot be on the same side of the starshade as the telescope at all during observations- even the blackest or shiniest known materials would then scatter too much sunlight toward the telescope. This constraint is already built into all the starshade mission concepts. With the Sun on the opposite side of the starshade from the telescope, sunlight can only reach the telescope by scattering around the starshade edges, or through holes within the starshade surface. Section 2.1.6 describes how micrometeor bombardment of the starshade after its launch will tend to create holes in its opaque membrane layers over its mission lifetime. Sunlight can enter this layered structure, scatter multiple times within it, and exit toward the telescope. The small combined area of the holes, high number of scatters, and high attenuation per scatter will reduce this

[35] *Martin Regehr and Stuart Shaklan, Reflection of Light from a Starshade, JPL internal memo 9/24/14.*

stray light source to insignificant levels. Sunlight can also scatter off droplets of exhaust propellant when the thrusters are fired to maintain the starshade position. This scattered light is expected to be too bright to permit imaging, but the thrusters will fire infrequently, with known times and durations, and standard engineering is expected to be sufficient to ensure that observations are paused during these intervals. This engineering will be described in more detail in Section 2.2.1 below.

This leaves the scatter of sunlight from the starshade edges. Reducing this to manageable levels is technology S-1 in this plan.

2.1.3 *STARSHADE SHAPE DETERMINATION*

We briefly describe here the method S5 uses to determine the optimal shape of the starshade for a given mission.[36] The flower shape of a starshade is a binary mask approximation of a radially symmetric apodization function that is designed to suppress light diffraction around the edges of the mask into the center of its shadow. There is an infinite family of flower-like shapes suitable for exoplanet finding. To find the best shape for a given mission, a complex shape function with hundreds of adjustable parameters is adopted, and linear optimization is used to choose the best parameter values. This optimization is driven to maximize starlight suppression within the telescope pupil, while meeting additional engineering and scientific constraints such as desired bandpass, starshade disk diameter and petal length limitations, and minimum feature sizes. This process is run iteratively. First, parametric studies with large numbers of approximate solutions are used to illustrate trends in performance. Then, some tens of potential designs are run through the optimization scheme to find candidates that meet all requirements. Finally, selected designs are rigorously verified to provide requisite starlight suppression at all points in the focal plane. We note in passing that apodization functions with simpler analytical forms exist (e.g. hypergaussian[37]), but have not been adopted for this plan.

There is a small amount of freedom in selecting the number of petals. The number of petals is only weakly bounded by optical performance. Too few petals and the approximations used to model performance slowly begin to become important. Too many petals require finer (less robust) petal tips and gaps, as well as more hardware to build and deploy. Minimum petal tip and gap widths are one of the constraints in the optimization. Figure 3 shows the optimized shape of a starshade petal and of the entire starshade.

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[36] *A fuller summary is given in the Exo-S final report, section 6.1, from which this is adapted.*
[37] *W. Cash, "Detection of Earth-like planets around nearby stars using a petal-shaped occulter", Nature vol. 442 pp. 51-3 (2006)..*

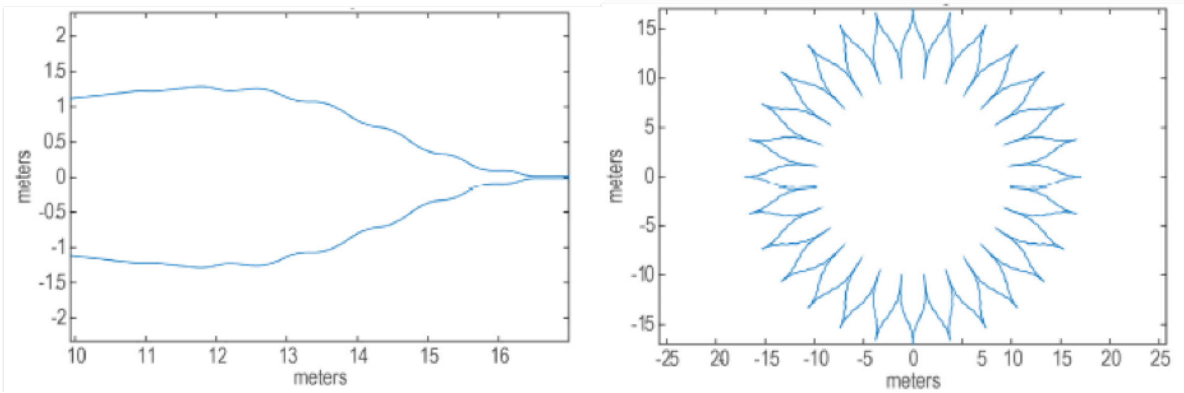

Figure 3: Left: optimized shape of Starshade Rendezvous petal. Right: Shape of the entire starshade. (From Exo-S report.)

For Starshade Rendezvous, the science constraints are the suppression and bandpass required.

Several different groups (JPL, NGAS, Princeton, Colorado) have developed and maintain optical simulation software that agree to high precision in predictions for given starshade shapes, giving confidence that they all calculate their modeled physics accurately.[38]

2.1.4 *ERROR BUDGET*

S5 maintains an error budget to model starshade performance and allocate tolerances between the several technologies and several assemblies. Figure 2 summarizes the error budget at a very high level, showing how it is used to allocate tolerances among the five technologies, other potential limiters of starshade mission performance, and performance margins.

At a lower level, S5 uses the starshade shape error budget to understand how different types of deformation contribute to photometric and systematic noise at the telescope, and set maximum allowable amplitudes for each type of deformation. Deformations can be either static (as-built) or dynamic (resulting from temporary stresses). Optical models that predict starshade performance in the presence of shape errors are used to populate the entries in the error budget.

Figure 4 shows an excerpt from the starshade shape error budget. Pictured at left is only one page showing the allocated errors in the as-built ('Manufactured') starshade: additional pages in the error budget contain the allocations at deployment, under dynamic inputs, and under thermal deformations. The starshade shape error budget also includes allocations of error for the formation flying, which considers the closed-loop performance in the relevant environment and is used to determine the lateral sensing KPP requirement.

One insight into starshade performance is that width-preserving deformations of the petals and out-of-plane deformations of the starshade reduce the achievable contrast only weakly.

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[38] Shaklan, S. B., Noecker, M. C., Glassman, T., et al., "Error budgeting and tolerancing of starshades for exoplanet detection," Proc. SPIE 7731, 77312G (2010).

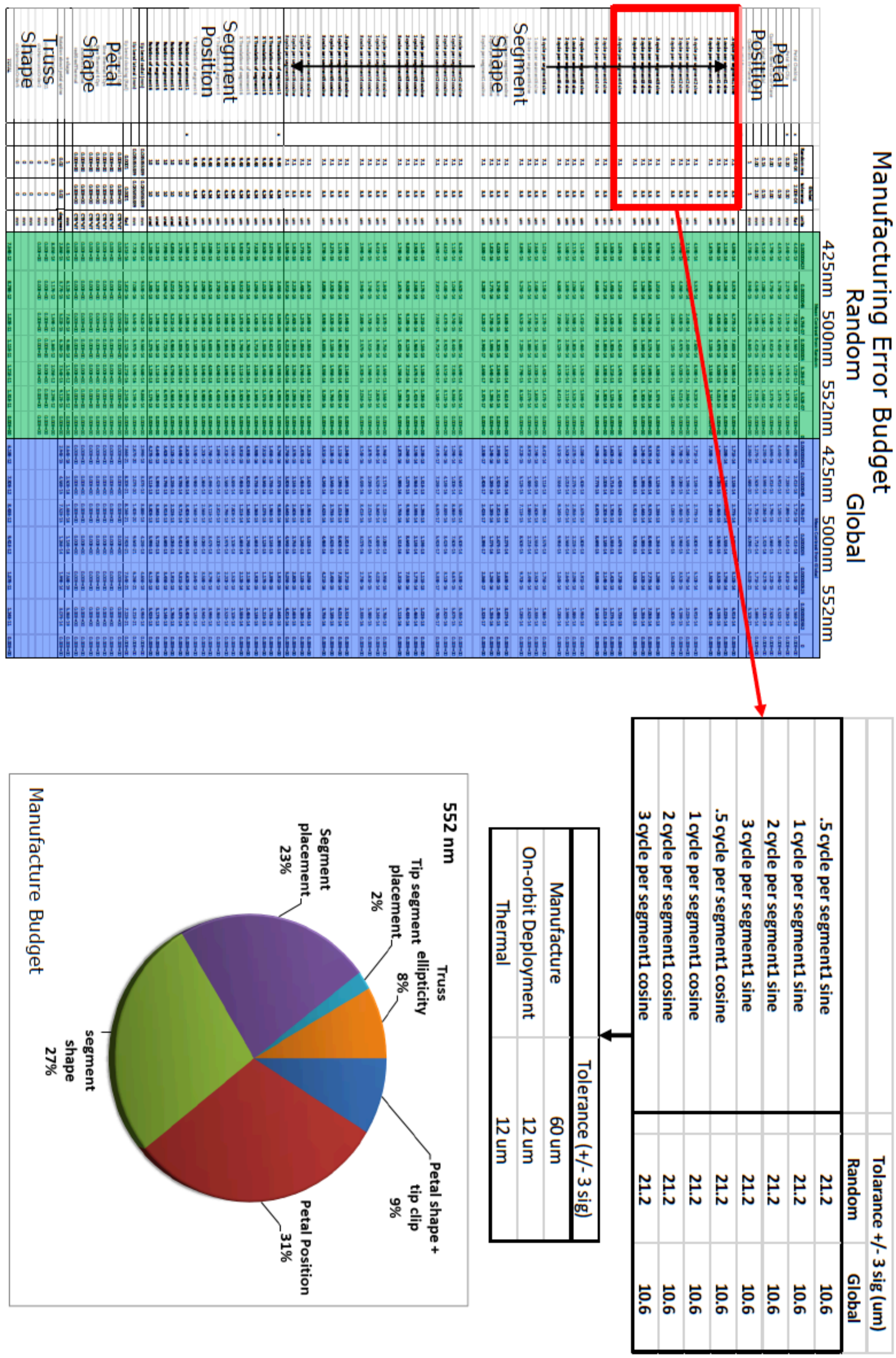

Figure 4: Starshade shape error budget.

2.1.5 *CONTRAST PERFORMANCE MODELING AND VALIDATION (S-2)*

The Starlight Suppression technology development plan has two main requirements:

1. Experimentally demonstrate light contrast to 10^{-10} at flight Fresnel numbers (8-20).
2. Experimentally validate the model sensitivity of contrast to key parameters and determine optical model uncertainty factors for the error budget.

Secondary goals are to establish confidence limits in the error budget and link its performance predictions to imaging simulations of a perturbed starshade.

The complication in ground-based verification of expected starlight contrast performance in space is not related to the differences between ground and space environments or between Earth's gravity and zero gravity. It arises from the sheer difference in optical baseline that can be tested on Earth relative to the space telescope baseline. In scalar diffraction theory, the optical performance of starshades of a given apodization is the same for all length scales, provided the Fresnel number is the same. This can be seen by study of the Fresnel diffraction integral describing the electric field transmitted through an aperture:

$$E_{occ}(\rho) = E_0 e^{\frac{2\pi i}{\lambda}z}\left\{1 - \frac{2\pi}{i\lambda z}\int_0^R A(r) J_0\left(\frac{2\pi r\rho}{\lambda z}\right) e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} r\,dr\right\}$$

Here r is the radial position on the starshade, λ is the light wavelength, z is the distance from starshade to telescope, ρ is the radial position at the telescope plane, and $A(r)$ is the starshade's amplitude transmission function. (Here Babinet's principle has been used to mathematically describe the optics of an obstacle by those of an identically sized aperture.) The Fresnel number $F = r^2/\lambda z$ appears in the kernel of the Fresnel propagator. If we rescale the equation by a factor s while preserving the Fresnel number ($\rho' = \rho/s, r' = r/s, z' = z/s^2$), we get:[39]

$$E_{occ}(\rho') = E_0 e^{\frac{2\pi i}{\lambda}z' s^2}\left\{1 - \frac{2\pi}{i\lambda z'}\int_0^{R'} A(sr') J_0\left(\frac{2\pi r'\rho'}{\lambda z'}\right) e^{\frac{\pi i}{\lambda z'}(r'^2+\rho'^2)} r'\,dr'\right\}$$

The equation is unchanged, except for the (uninteresting) overall phase factor, and the scaling of the amplitude transmission function by s. This shows that smaller masks operating at smaller baselines have the same scalar diffraction behavior as large masks at large baselines.

Ground-based testing practicalities limit test starshade sizes to the centimeter scale. Scalar diffraction can be applied to an optical system when polarization effects are negligible. Modeling has shown that for a full-scale starshade, polarization effects enter at the 10^{-15} contrast level, well below desired requirements. The more precise vector diffraction theory diverges from scalar diffraction theory in the vicinity of the edges and fine features in starshades. Vector diffraction effects therefore play an outsized role in contrast performance in small ground-based starshades compared to flight-scale starshades. The S5 development of starlight contrast technology will quantify these effects and/or devise small-scale test articles that minimize their impact. If small starshades demonstrate

[39] *D. Sirbu et al., "Diffractive analysis of limits of an occulter experiment", Proc. SPIE vol. 9143, art. no. 2P (2014).*

performance requirements even with the outsized vector diffraction effects, full-scale starshades certainly will.

Figure 5 shows the Frick optical testbed at Princeton, where the contrast and suppression of the starshade masks will be measured. The testbed is 80 meters long, with a laser station at one end illuminating the starshade mask 27 meters away with a diverging 638-nm diode laser beam (stellar illumination would be essentially planar at the starshade, but the effect of the diverging beam is equivalent to a small change of Fresnel number). The light then propagates another 50 meters to the camera station, where a detector measures the intensity profile at either the pupil plane or image plane, as needed. The aperture of the camera is sized to reproduce the WFIRST aperture at the reduced scale. The testbed is enclosed to exclude stray light and drafts. It is also thermally insulated to minimize internal air currents due to thermal gradients.

Figure 5: Left: The Princeton Frick testbed. Right: a starshade mask as mounted in the testbed.

The baseline plan is for the test masks to be manufactured in the Microdevices Laboratory (MDL) at JPL, using a complex, multi-step process involving Deep Reactive Ion (DRI) etching of both sides of a 4" silicon-on-insulator (SOI) wafer. The process has developed over the past three years, and may continue to develop during the S5 execution. To date, unreliability of the STS etcher used by the MDL has complicated the refinement of the fabrication process, but JPL has recently acquired an Oxford 100 Cobra etcher for future work. The MDL also houses scanning electron and optical microscopes for the characterization of the mask shapes and defects before shipment to Princeton for optical testing. Figure 6 shows a cross-section of the edge of a mask as seen by the SEM. This mask includes a silicon nitride membrane overlaying the silicon, but the presence of this layer is one design parameter being explored by S5.

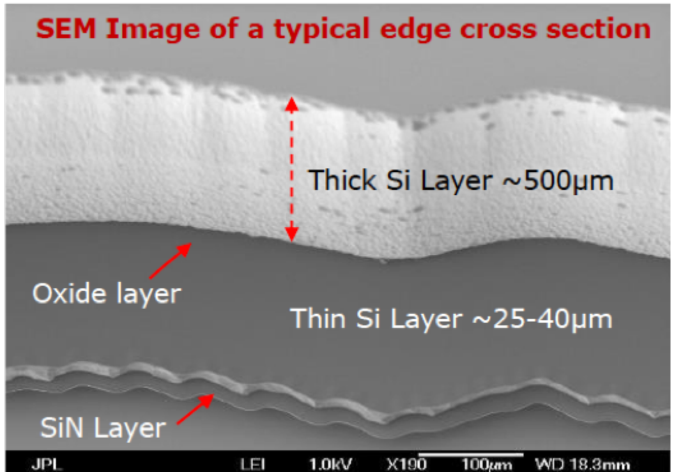

Figure 6: Cross section of typical mask edge.

The acceptable tolerances in the test mask shape for a given suppression performance scale linearly with the mask size. Thus, the 10's of micron tolerances for a 30-meter scale starshade scale to 10's of nanometer tolerances in a test mask a few centimeters wide. These are tight tolerances, at the edge of current technology. Table 3 shows how the design parameters and optical performance of masks made at MDL have developed over the past few years. The experimentally achieved suppression and number of defects have both improved significantly during this period. Current estimates to performance limitations suggest that small features at the innermost valleys will show significant vector diffraction effects. Studies are underway to design around this issue.

Subscale mask production is treated as a significant risk to reaching TRL5. S5 includes a contingency plan to acquire masks from outside vendors as a backup, should the MDL be unable to produce test masks to the needed yield and schedule. An RFI was recently issued, leading to four outside vendors expressing interest in a mask fabrication subcontract. An RFP is pending.

The starlight suppression activity will have two main thrusts: to show that the understanding of the optical performance of starshade is sufficient to predict $1x10^{-10}$ instrument contrast for the flight article by demonstrating $1x10^{-10}$ instrument contrast in a small-scale ground article, and to validate the optical models that relate shape errors to contrast performance by measuring the reduction in contrast for starshades with deliberate shape errors with 25% accuracy. S5 maintains three top-level milestones for these activities.

Table 3: Progress of mask design to date.

Year	Fresnel Number	Starshade Diameter (cm)	Smallest Feature (µm)	Contact or Direct e-beam Lithography	SOI Layer Thickness (µm)	Si_3N_4 Membrane	Coating	Defects	Results
2015	500	9	?	Contact Lith	?	No	None	Rough edges, over and underetch artifacts, blocked inner tips, pinholes up to 70 um.	Sirbu et al Apllied Optics 55, 6083, (2016).
2016	27	5	< 1	Contact Lith	25-40	No	Al	"Dog ear" artifacts 4x10 microns on most petals, blocked inner tips, under-etch.	Kim et al Proc. SPIE 10400 (2017).
2017	27	5	7.5	Contact Lith	25-40	Yes	Al	Overetch 400 nm, 50x30 um pinhole, Al surface shows 'blisters' from XeF2 processing.	Testbed achieved ~1e-8 contrast, Harness et al Proc. SPIE 10400 (2017).
2017 Nov DW3	27	5	7.5	Direct Write	25-40	Yes	Au	Overetch ~100nm or better, one defect with 400 sq. microns, total defects ~850 sq. microns.	Installed at Princeton, but accidentally broken. Preliminary data before break showed ~4e-8 suppression.
2018 Jan DW9	27	5	7.5	Direct Write	7	No	Au	Edge roughness ~100nm. Overetch ~100nm. Defect areas ~300 sq. microns.	Preliminary suppression of ~6e-8 achieved.
2018 Jun DW11	14	5	16	Direct Write	7	No	Au	Overetch ~150nm. Defect areas ~370 sq. microns.	Preliminary suppression ~1e-8, contrast ~2e-10 achieved. Limited by vector diffraction rates.
2018 Jul DW13	14	5	16	Direct Write	4	No	Au	Edge roughness ~30nm. Overetch ~~275nm. Defect areas ~60 sq. microns.	Preliminary suppression ~1e-8, contrast ~2e-10 achieved. Limited by overetch.
2018 Aug DW14	14	5	16	Direct Write	2	No	Au	Edge roughness ~30nm. Overetch ~300nm. Defect areas ~20 sq. microns.	Preliminary suppression ~1e-8, contrast ~2e-10 achieved. Limited by overetch.

- MILESTONE 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 ≤ 15. (1/28/2019)

Previous development of small-scale masks depicted in Table 3 has been towards this first milestone. The light wavelength is nominally 600 nm.

- MILESTONE 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)

Once a mask has demonstrated performance consistent with Milestone 1A above, the Frick testbed will then substitute a set of light sources spanning the 10% bandwidth into the testbed and remeasure the contrast of that same mask over a set of wavelengths. Each source will itself be narrowband, and measurement at each wavelength will be done separately, but without modifying the positions of the starshade, camera, and light source pinhole.

- Milestones 1A and 1B together satisfy KPP1. For both these milestones, the inner working angle of the mask is defined to be the point where innermost radius where its apodization function reaches its maximum value, i.e. at the inner end of the supporting ribs.
- MILESTONE 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)

Once Milestone 1B has been accomplished a succession of new masks with deliberate errors will be fabricated and measured in the testbed. These measurements will be at one narrowband wavelength. The specific shape errors that will be induced are given in Table 4 below. These masks will be manufactured and tested on a schedule of roughly one mask every four weeks.

Table 4: Small-scale starshade masks for Milestone 2

Mask Function	Description	Pertubation	Pertubation *2
Single Petal Radial Position Error	Petal shifts outward	X	X
Disk scale	All petal shifts outward	X	X
Edge Sine Wave	N cycles base to tip	X	X
Petal Tips	Create mask with tips	X	
Edge Segment Displacement	Normal to edge	X	X
Combination segment shift and sine wave	Observe interference	X	X

Milestone 2 satisfies KPP2. Together, milestones 1A, 1B, and 2 bring the starlight suppression technology S-2 to TRL5.

The S5 plan includes continued testing of starshade masks in the Princeton testbed after completing Milestone 2, to further refine the error budget towards TRL6.

The starshade small-scale optical masks have been judged by JPL's IECO to have EAR classification EAR99. Under this classification they can be transported and tested within the United States and other nations, and by U.S. and foreign nationals, excepting the nations on the Sanctioned Destinations list: Cuba, Iran, North Korea, Sudan, and Syria.

2.1.6 *OPACITY MODELING AND REQUIREMENTS*

S5 assumes that to build, launch, and deploy a starshade that is initially opaque enough not to scatter sunlight toward the telescope though gaps internal to its optical edge will require straightforward engineering. It is less straightforwardly answered whether holes created in the starshade after deployment by micrometeoroid bombardment will, over the mission lifetime, leak enough sunlight to significantly impair starshade performance.

An optical scattering model that approximates the starshade optical shield by two layers of black Kapton separated by a gap that is partially filled by a foam spacer was analyzed to estimate sunlight leakage.[40] This model indicated that the leaked sunlight would have magnitude fainter than V=34.5 if the total area of holes were less than about 30-250 square centimeters, depending upon the foam's transmittance. A separate analysis of the expected micrometeoroid rate suggests that the rate of hole generation over the starshade will be many orders of magnitude less than this per year.[41] S5 therefore anticipates that sunlight leakage through micrometeoroid holes will not be an issue. Nevertheless, S5 will refine these analyses in concert with the mechanical development of the optical shield to ensure that it remains not an issue.

2.1.7 *SCATTERED SUNLIGHT FOR PETAL EDGES (S-1)*

The edges scatter sunlight towards the telescope via a combination of diffraction, diffuse reflection, and specular reflection.[42] When all these scattering mechanisms are considered together, the telescope will see the scattered sunlight coming mainly from localized regions on a few petals where the optical edge is aligned for specular reflection. These will appear as two broad lobes due to the telescope's finite spatial resolution (see Figure 7). An integration model used for the Exo-S study showed that these two scatter lobes would increase the integration time for exoplanets at the inner working angle by 25% if their magnitude was V=25. This model assumed an exozodi density 3x the local zodi density (which when added to the local zodi surface brightness increases it 7x). The effect of solar glint on integration time decreases with increasing distance from the starshade.

Any practical optical edge will have a finite radius of curvature, and so will have some surface area that by either specular of diffuse reflection can scatter sunlight toward the telescope. However, even if the edge could be made infinitesimally sharp, diffraction at the edge sets a fundamental lower limit to the amount of scattered light. Any reflection from a rounded edge will, to first order, add to the diffracted light. The sunlight at the starshade is incoherent over the dimensions of the starshade, so it is not necessary to model diffraction of sunlight over the starshade as a whole in the same way as for starlight; it is sufficient to calculate the amount of diffracted light per unit length of edge as a function of edge orientation and illumination, and integrate this around the circumference of the starshade. By this we learn that diffraction alone creates lobes of magnitude V=25.6. Therefore, the scatter due to reflection must be at an even lower level.

[40] *S. Shaklan et al., "Error budgets for the Exoplanet Starshade (Exo-S) probe-class mission study", Proc. SPIE vol. 9605, art. no. 96050Z (2015).*
[41] *J. Arenberg et al., "Effects of scattered light on the performance of the New Worlds starshade", Proc. SPIE vol. 6693, art. no. 66931E (2007).*
[42] *S. Martin et al., "Starshade optical edge modeling, requirements, and laboratory tests", Proc. SPIE vol. 8864, art. no. 88641A (2013).*

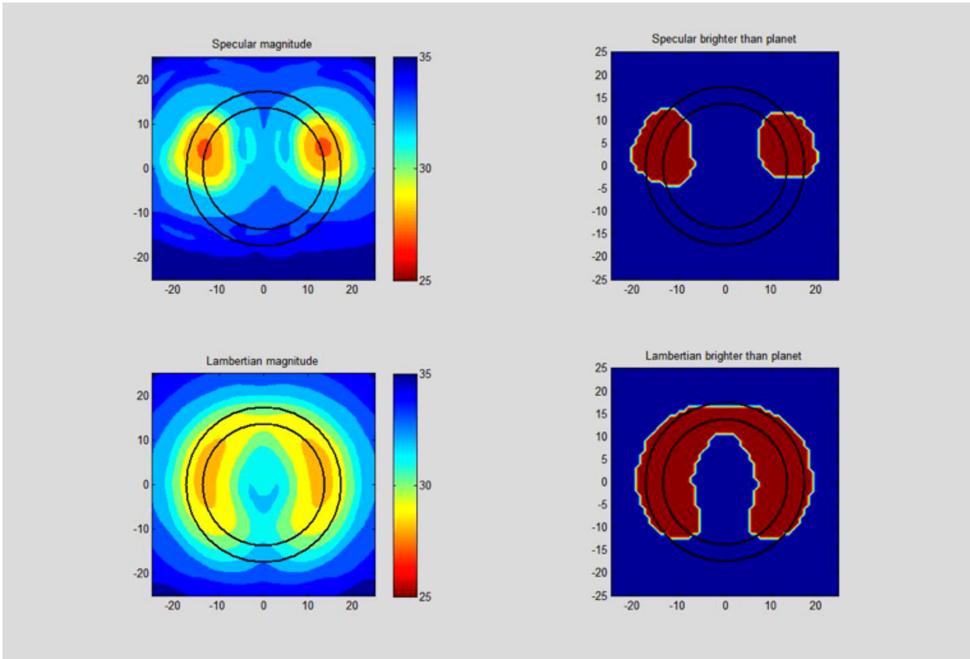

Figure 7: Solar scatter from starshade as seen by WFIRST.

JPL maintains a '2-D' scatterometer to measure the total scatter of edge samples at varying angles and polarizations. Several candidate edges in small-scale test coupons were tested in the 2-D scatterometer to investigate the tradeoff between relatively sharp and shiny edges and relatively blunt and dark edges (blunt and shiny edges are an obvious poor choice as they present a large reflecting area to the telescope; attempts to make sharp edges dark tended to render them blunt). From these tests, etched amorphous metal was baselined as the only edge design that could meet the scatter requirements over the entire range of angles. Figure 8 shows the results of the 2-D scatterometer tests for the edge materials tested.

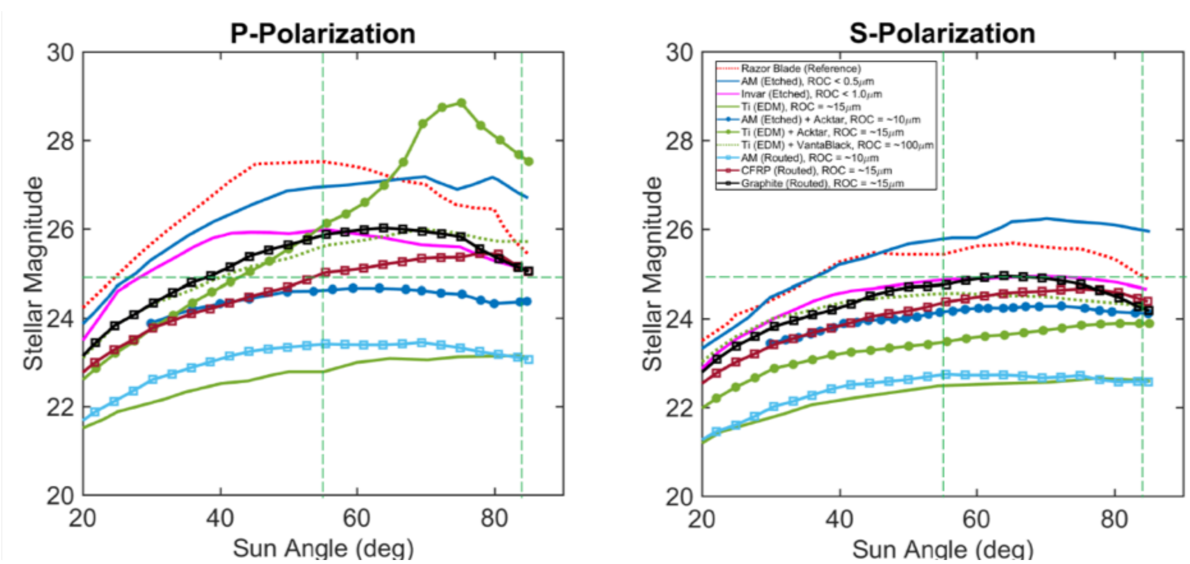

Figure 8: Measured solar scatter, referenced to magnitude at telescope, for candidate edge materials tested. The vertical dashed lines show the allowable limits of incident Sun angles in the Starshade Rendezvous mission. The horizontal dashed line shows the minimum acceptable magnitude of scatter.

The performance of small-scale etched amorphous metal edges in the 2-D scatterometer demonstrates that the edge scatter technology is at TRL4. To reach TRL5 it is necessary to demonstrate the minimum performance of a medium fidelity assembly in a relevant environment and characterize its life limiters and failure modes. There are two relevant environments for the optical edge that most stress the edge in ways that could limit its optical performance. One is the furling/storage/launch/deployment process, in which the optical edges will be flexed with the petals into the stowed configuration, stored in a stressed state during which it could creep or tear, subjected to the shaking of launch and the dust contamination that shakes loose from the fairing during launch, and then straightened during petal deployment. The other relevant environment is the thermal cycling that the edges will undergo as the incident sunlight angle at the starshade varies with its travels. We note here that changes to the edges that impact starlight suppression are considered separately in 2.1.5.

The space environment is not anticipated to be a relevant/stressing environment. The optical behavior of the edges barely changes between operation in air and vacuum at visible wavelengths. The rates of dust accumulation and damage by micrometeorite bombardment are also expected to be extremely small over the two year lifetime of the Starshade Rendezvous mission. Provided that the tests show thermal cycling does not damage the optical edge, these are expected to be the life limiters. The S5 plan includes further engineering study of these effects in FY21.

S5 plans to use the 2-D scatterometer (Figure 9) for verification of angular scatter of small coupons and, if necessary, sections taken from full-scale test article over wide ranges of angle, wavelength, and polarization. In order to characterize an entire edge, a new fixed-angle scatterometer will be built for testing of edges within full-scale petal subassemblies at a limited range of angles and wavelengths and polarizations. This fixed angle scatterometer will not be able to fully characterize the scatter of sunlight toward the telescope by an edge segment. Rather, it will make measurements at fixed angles of full edge segments along with measurements of 'witness' coupons; the witness coupons can then be measured for full performance in the full-angle scatterometer as proxies for the full edge segments, and the fixed-angle scatterometer can then be used to search for changes in the edge scatter caused by furling and thermal cycling. The new scatterometer may be built at JPL or under subcontract to an outside vendor.

The optical edges themselves (edge segments and tips) are subassemblies of the starshade petal assembly. The prototype edge articles will be acquired and tested within the mechanical technology development plan described in Section 2.3.4. The fixed angle scatterometer will be delivered to the mechanical team after its fabrication and commissioning.

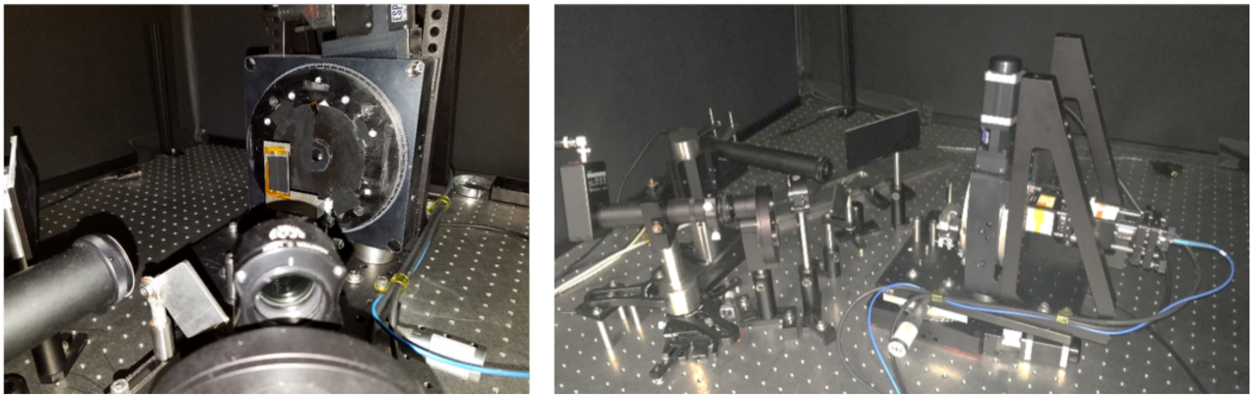

Figure 9: Edge scatterometer at JPL.

S5 maintains a single top-level milestone to bring the solar scatter technology S-1 to TRL5:

- MILESTONE 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)

The verification method for this milestone is to first calibrate the fixed-angle scatterometer by measuring edge coupons using both the fixed-angle scatterometer and the 2-D scatterometer. The assembled edge segment will be measured along its length before and after the thermal and bending cycles to see if any change has occurred. Any changes/damage will be studied further by extracting the section of edge and studying it visually using an SEM and also in the 2-D scatterometer to quantify the change in performance. The thermal and deploy cycles are performed on the same edge segments fabricated for edge shape accuracy described in section 2.3.4 below.

The optical edge scatter technology itself is not ITAR or EAR classified. When incorporated into a petal assembly its export is constrained by the export classification of the petal assembly.

2.1.8 *IMAGE SIMULATION AND PROCESSING FOR PLANET EXTRACTION*

S5 is also developing software that simulates images of exoplanets seen with realistic estimates of starshade KPPs such as instrument contrast and solar glint, as well as astrophysical parameters such as exozodiacal dust. This software is an engineering tool to assist in evaluation of the impact of various terms in the error budget on the ability to do exoplanet science. Examples of images produced by the imaging simulation are shown in Figure 10 below. In the figure, the 'Nominal SS' case shows the $4x10^{-12}$ residual starlight for a starshade with no mechanical shape errors, micrometeoroid holes, or lateral position offset. The '1e-10 SS' case shows the residual starlight with those factors included.

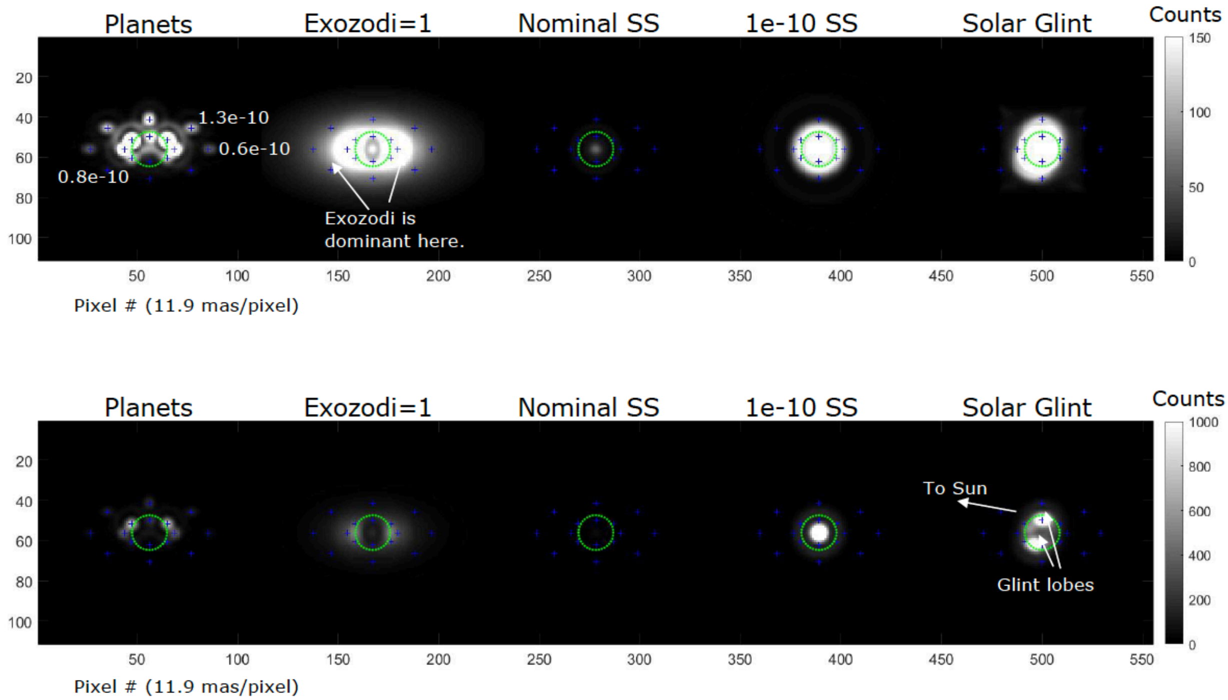

Figure 10: Sample images from the S5 imaging simulator for the WFIRST Starshade Rendezvous mission.

2.1.9 *SUMMARY OF OPTICAL SCHEDULE*

Figure 11: summarizes the optical technology milestones of S5.

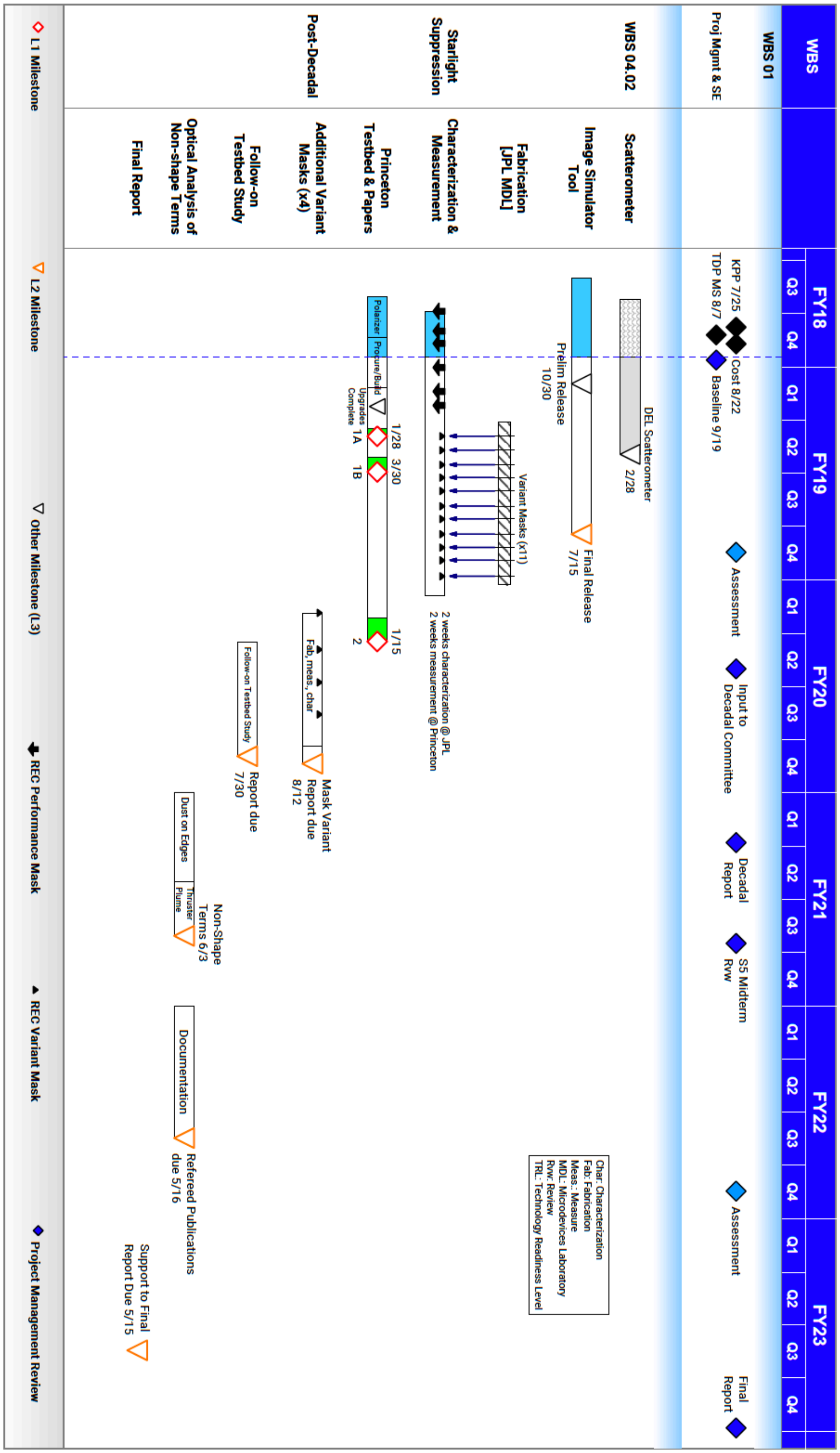

Figure 11: Top level summary schedule for starshade optical activities.

2.1.10 *OPTICAL TECHNOLOGY RISKS*

The risks that are currently identified to optical technology development are listed in Table 5. The highest risks are associated with the demonstration of starlight suppression in the Princeton testbed.

Table 5: Optical technology development risks

Risk ID	Risk Title	Likelihood (1-5)	Consequence (1-5)	Rating	Possible Mitigation
2	Multiple scatter of sunlight from petal	3	3	Med	Undertake study of multiple scattering of sunlight by starshade towards telescope.
3	Solar scatter KPP revision	2	3	Low	
4	Solar scatter increases after I&T	2	3	Low	Effort underway to characterize sensitivity. Need to understand launch fairing env. May need to request extra cleanliness. Before launch edges can be protected with peel wat coating under development as an SBIR.
5	Princeton testbed limits contrast performance	3	4	Med	Implement facility upgrades to address most likely influences on performance. Continue investigation of alternate facilities.
6	LDL mask fab limits test bed performance	3	4	Med	Find and use alternative mask vendors.
9	Stray light through micrometeorite holes	1	3	Low	Early assy level testing at Northrup to validate models and model multiple reflections. If baseline design insufficient, modify design (e.g. add layers).
12	MDL etcher unavailable	2	4	Med	Make sure that S5 has adequate priority in MDL queue. Push to ensure regular maintenance of etcher. Pursue alternate mask vendors.

2.2 FORMATION SENSING AND CONTROL

Formation flying encompasses the functionality that maneuvers the starshade into the correct position between the telescope and the target star and keeps it there within required tolerances. The main functional components required for formation flying are:

- thrusters on the starshade for positioning and attitude control,
- ranging transponders on the starshade and telescope for measuring starshade-telescope separation and for communication of positioning commands between the telescope and starshade,
- one or more LED or laser beacons on the starshade for sensing by the telescope after retargeting maneuvers, and
- a lateral position sensor on the telescope for measuring starshade misalignment from the telescope-star axis during science observations.

Use of existing ground-based DSN stations is also required after launch of the starshade to obtain initial absolute position information of the starshade and telescope needed to initialize the formation flying, and potentially in contingency scenarios.

As described in Section 1.3.3, the formation flying needs to be at TRL5 early enough that WFIRST can be designed to be starshade compatible. The development to TRL5 for this technology is accelerated to this end.

2.2.1 *CONCEPT OF OPERATIONS AND ACQUISITION SEQUENCE*

The requirements on the starshade's lateral and axial position and orientation relative to the telescope were derived in Section 1.3.1, and are given in Table 1. The starshade must first reach this relative position ('acquisition') before then maintaining it for the duration of an exoplanet observation ('science'). The starshade must additionally execute its maneuvers in a way that does not impact the imaging capabilities of the telescope. Figure 12 graphically depicts the concept of operations (CONOPS) for the starshade mission. It contains four operational phases:

1. **Initialization:** This phase spans the period from launch of the starshade to first detection of the starshade by a starshade acquisition camera (SAC, similar to a star tracker) on the telescope. The starshade will be launched into an Earth/Sun L2 orbit to rendezvous with the WFIRST telescope already there, and the telescope will need to 'find' the starshade for the first time. Ground-based absolute orbital determination of both the telescope and starshade are used to issue retargeting commands to the starshade to move it from its initial orbit to alignment between the telescope the first target star to within 100 km absolute accuracy of both telescope and starshade, with the starshade oriented toward the telescope to within a small angle. At the close of this phase, the beacon on the starshade will be visible within the 3,000 mas FOV of the SAC on the telescope.
2. **Acquisition:** This phase spans the period from first detection of the starshade by the telescope star tracker at the end of the initialization phase to first capture of the starshade within the lateral and axial position requirements. The telescope, which is already pointing at a target star, determines the offset of the starshade from the line of sight by observing the starshade's beacon initially using the SAC and then with the direct imager, these having coarse and medium sensitivity respectively. Course corrections are sent to the starshade to bring it onto the line of sight between the telescope and the target star.
3. **Science:** This phase spans the duration of any observations of an exoplanetary system, from the end of the acquisition phase to the beginning of a retargeting phase. The lateral position of the starshade relative to the telescope/star axis is sensed using the leakage of out-of-science-passband starlight around the starshade, as sensed by the WFIRST LOWFS system. The starshade may possibly be slowly spinning around its optical axis during exoplanet observations in order to average out glint and residual diffraction artifacts.
4. **Retargeting:** This phase is similar to the initialization phase, except that it begins at the end of a science phase and repositions the starshade to the next target star in the Starshade Rendezvous mission.

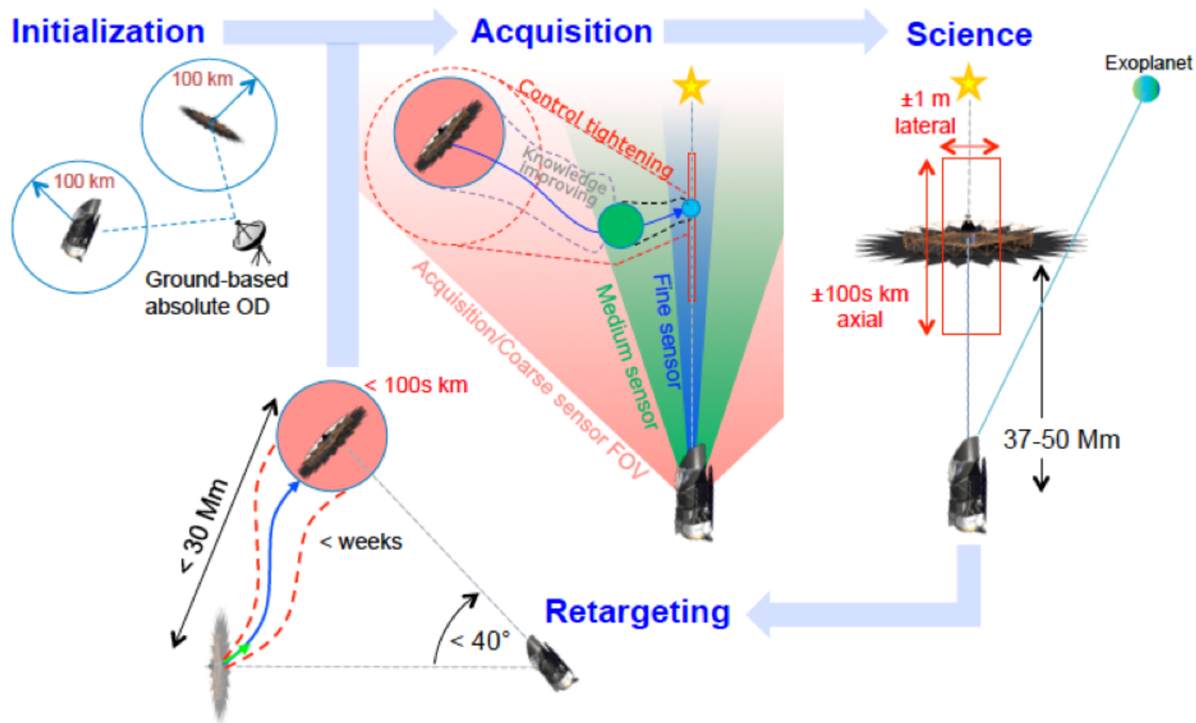

Figure 12: Overview of starshade Conops.

2.2.2 *LATERAL SENSING (S-3)*

The only technology that must be developed in order to bring the formation flying to TRL5 is the lateral sensing during the science phase of the conops. Axial distance sensing over tens of megameter distances to hundreds of meters accuracy can be straightforwardly achieved using S-band ranging transponders. The disturbances to the position of the starshade relative to the telescope/star axis are dominated by gravity gradient forces and solar pressure with a worst-case relative acceleration of ≤1 μg (WFIRST value; for HabEx the worst case will be ~3x greater), and to maintain lateral positioning to within 1 meter requires brief thruster application only about once every 600 seconds, much longer for the axial positioning. Lateral position control to better than 1 m in a ≤20 μg disturbance requirement is regularly done during spacecraft docking maneuvers in low Earth orbit. All the hardware needed for formation flying is also already flight-qualified. The same scaling relations from flight-scale to ground-scale optical testing given in Section 2.1.5 also apply here; thus, the needed optical performance is readily verified in ground-based tests, and formation flying algorithms that use these signals can be adequately tested using model simulations.

Propellant droplets in the thruster exhaust will scatter significant levels of sunlight toward the telescope during the thruster operation, which will last for a few seconds once every several minutes;[43] this can be dealt with by appropriate shuttering or gain control of the telescope cameras and does not require new technology development.

The physics underlying the S5 concept for lateral position sensing of the starshade is simple. The starshade apodization suppresses the Poisson spot and creates a deep (1×10^{-10}) shadow, but only over a limited range of light wavelengths. Outside the starshade stopband, the Poisson spot rapidly

[43] *S. Martin, "An estimate of sunlight scattering from the thruster plume", JPL internal memo.*

increases in brightness to the 10^{-4}-10^{-3} level. This spot can be used as a lateral offset signal when sensed with a pupil imager, such as those used in coronagraphs. The left side of Figure 13 shows how the light intensity in the starshade shadow increases dramatically outside the starshade stopband, to both the red and blue. The diffracted structure within the shadow is rather complex; however, within the central few meters the shadow has a bright Poisson spot marking its center, with the brightness then smoothly increasing radially. The right side of Figure 13 shows the shadow, with the WFIRST aperture shown for scale. The lateral sensing concept is for WFIRST to store a library of images generated for a matrix of starshade offset directions and locations as a reference to compare to the actual measured shadow of the starshade at the sensing wavelength.[44] The left figure in the inset of Figure 13 depicts one such reference image, and the right figure in the inset depicts a detected image with noise. The reference image most closely matching the detected image provides the measurement of offset direction and distance that would be used by the formation flying servo. The specific algorithm used to match measured image to library image will be one outcome of this technology development activity.

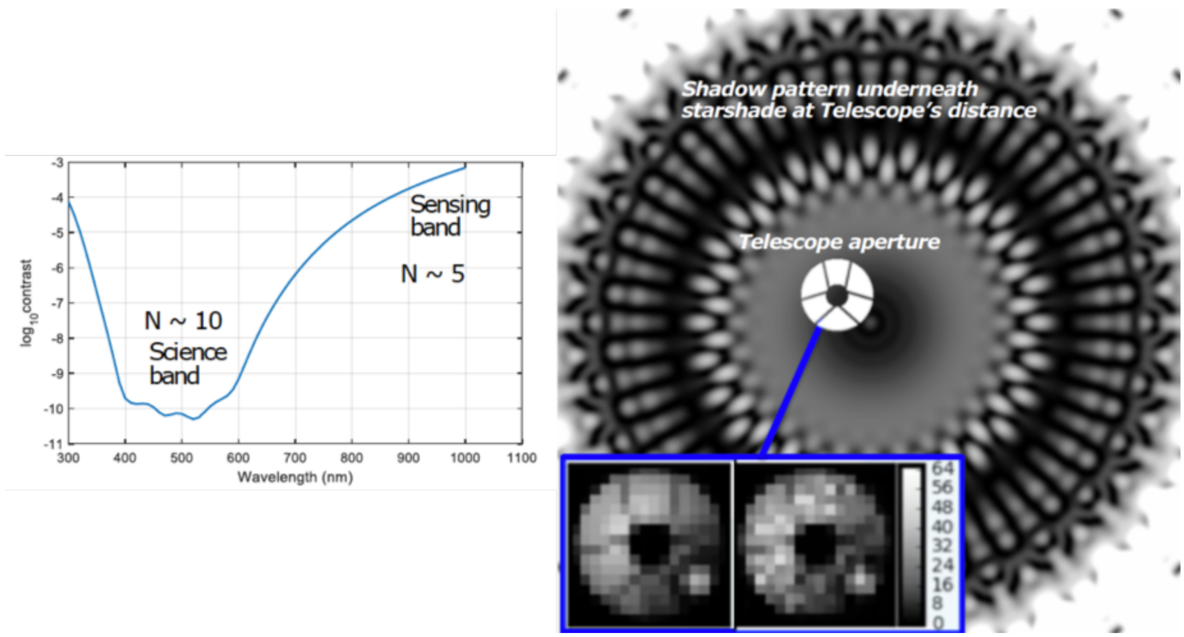

Figure 13: Left, suppression vs. wavelength of starshade, showing both science and sensing regions. Right, modeled starshade suppression pattern in sensing band with WFIRST aperture shown for scale. Inset, predicted lateral sensing image at WFIRST pupil plane, with and without simulated noise.

The formation flying technology development plan relies upon one key facility, the Starshade Lateral Alignment Testbed Experiment (SLATE) at JPL that has been built for this purpose. SLATE is conceptually similar to the Princeton testbed used to verify the optical models of starshade suppression in the science band; however, since the suppression performance is greatly relaxed for later sensing, the mask dimensions need not be as precise, and so smaller masks in a shorter testbed may be used. Figure 14 shows the SLATE layout. As currently built, the SLATE measures optical contrast over a laser bandwidth of a few nanometers. This is sufficient to validate the optical model, but not to generate images like those the WFIRST LOWFS would measure with its larger

[44] *"Precise starshade stationkeeping and pointing with a Zernike wavefront sensor" Michael Bottom et al., Proc. SPIE 10400 Techniques and Instrumentation for Detection of Exoplanets VIII, 2017*

bandpasses. An optical model validated using measurements with a narrowband light source is considered adequate in S5 for generating images measured within the LOWFS sensor band. In flight, with the target stellar spectrum modified by the starshade and the quantum efficiency of the sensor modifying the remaining spectrum, the LOWFS will detect light over a limited but broader band up to ~50 nm wide. A broadband source and appropriate filters can be installed in SLATE for higher fidelity validation leading to TRL6.

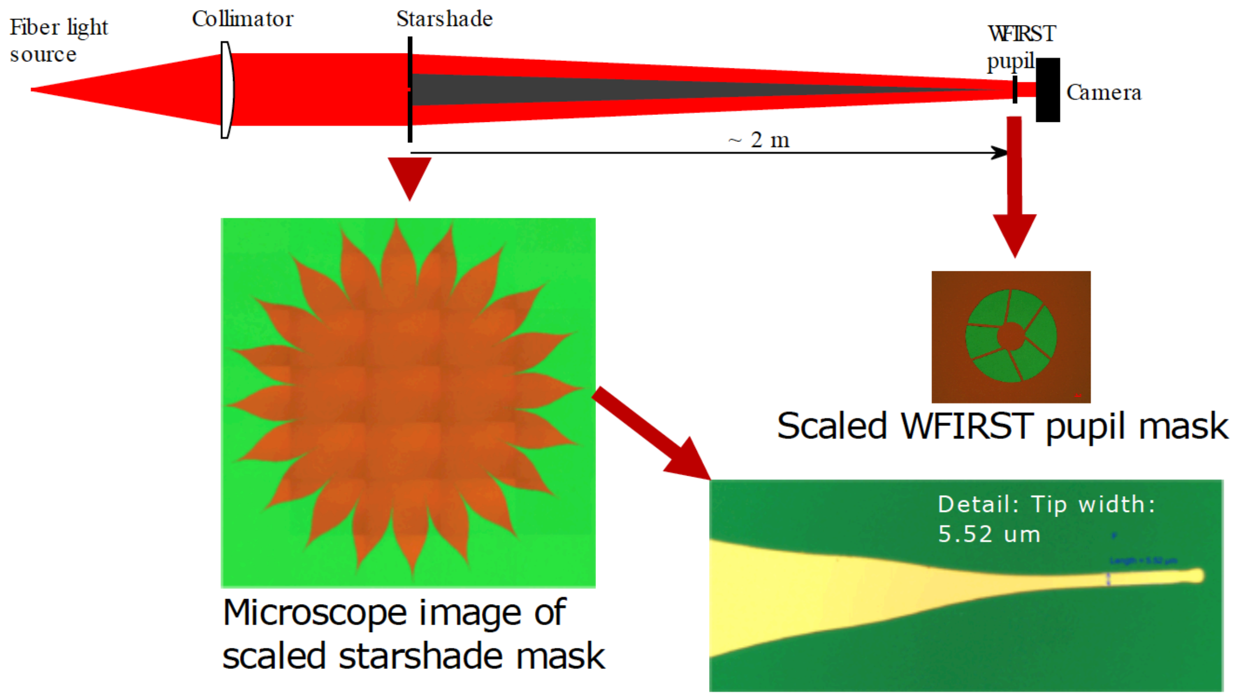

Figure 14: SLATE layout.

The SLATE testbed produces images with the correct structure of the starshade shadow at sensing wavelengths, but the suppression at the shadow center is limited by small wavefront errors within the optical system of the beam launcher and starshade mask substrate. These errors produce background light within the shadow such that the shadow contrast is at the ~10^{-3} level and not at the 10^{-4} level expected for flight (Figure 15). However, the signal from the starshade can be increased above the background by an adjustment to the Fresnel number from 5 (flight value) to 4.5, without affecting the appearance of the Poisson spot. This adjustment has been made rather than have very expensive optics built with nanometer level wavefront error. The key parameter is to reach a SNR in SLATE within the Poisson spot identical to that expected in flight and this will be achieved by adjusting the illuminating flux.

The plan to bring the lateral position sensing to TRL5 involves three main tasks, to be executed in sequence. First, the optical model that predicts the out-of-band suppression pattern will be verified by comparison to images collected in the SLATE. Next, the algorithm that infers lateral offset distance by comparison to an offset image library will be tested by applying it to images collected at the SLATE with known offset and the flight SNR. Finally, a MATLAB model that simulates the lateral control servo using the lateral sensing algorithm will be run to demonstrate that lateral position control. This model will assume the WFIRST LOWFS end of mission performance parameters apply, and will use as the relevant/stressing environment a combination of gravity gradient and solar radiation pressure forces on the telescope and starshade with a total disturbance ≤1 μg at timescales long compared to the transit of the starshade through the requirement tolerance range. This model contains, besides the environmental variables, a flight guidance and control (GNC) simulation. Within this simulation, the rest of the starshade itself forms part of the relevant environment for the purpose of validating the model of lateral control performance; for this purpose, it is assumed that the starshade is a rigid body of mass ≥1200 kg using hydrazine MR-103M minimum impulse thrusters.

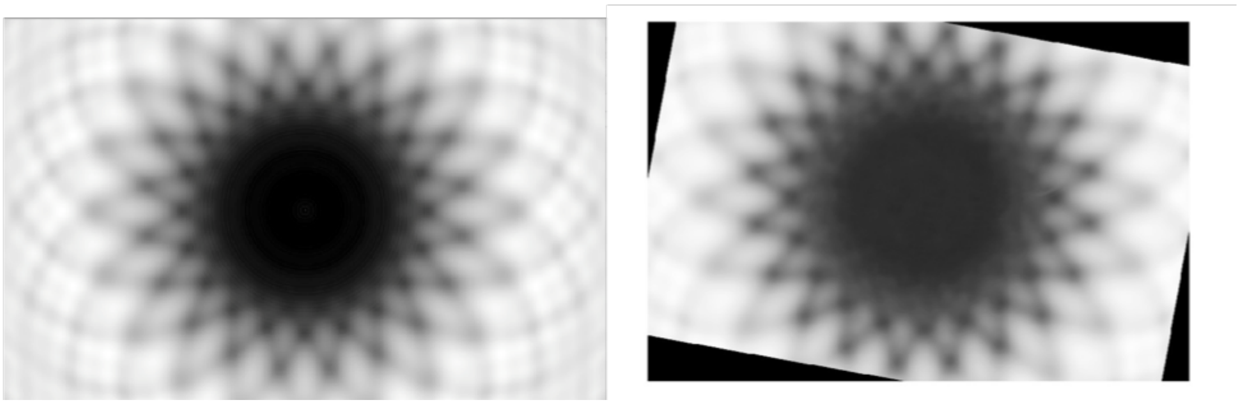

Figure 15: Left, starshade shadow in sensing band predicted by optical model. Right, shadow measured in SLATE.

Table 6 shows the baseline schedule for the formation flying technology development. It has a single top-level milestone that brings the lateral sensing technology S-4 to TRL5.

- MILESTONE 4: Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral position offset sensitivity to a flight equivalent of 30cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ±1m. (11/14/2018)

Table 6: Schedule for formation flying activities and milestones.

ID	L1 L2	#Re Del	MS#	Task Name	% Complete	Duration	Start	Finish	Predecessors	Successors
5				**Starshade S5 to TRL-5**	**4%**	**1228 day**	**Tue 5/1/18**	**Mon 9/25/23**		
6				**Project Management**	**0%**	**1228 day**	**Tue 5/1/18**	**Mon 9/25/23**		
54				**Formation Flying**	**22%**	**166 days**	**Tue 5/1/18**	**Fri 1/25/19**		
55				**Formation Flying- Simulations**	**0%**	**88 days**	**Tue 5/1/18**	**Tue 9/18/18**		
56				Starshade GNC Science Simulation w/ algorithms	0%	72 days	Tue 5/1/18	Wed 8/22/18		58
57		REC		REC Updated Matlab noise model [from Testbed]	0%	0 days	Tue 9/4/18	Tue 9/4/18	64	
58				Formation Flying: Monte Carlo Simulations	0%	16 days	Thu 8/23/18	Tue 9/18/18	56	66
59				**Formation Flying- Testbed Work**	**83%**	**79 days**	**Tue 5/1/18**	**Tue 9/4/18**		
60				Complete rebuild of testbed	100%	12 days	Tue 5/1/18	Thu 5/17/18	1	61
61				Obtain and analyze images [compared to model]	100%	25 days	Fri 5/18/18	Wed 6/27/18	60	62
62				Flying Formation sensor demonstration [motion stage]	100%	21 days	Thu 6/28/18	Tue 7/31/18	61	
63				Update Matlab noise model	0%	12 days	Wed 8/15/18	Tue 9/4/18		64
64	L2	DEL		DEL Updated Matlab noise model [to Simulation]	0%	0 days	Tue 9/4/18	Tue 9/4/18	63	57
65				**Formation Flying- Reporting Activities**	**0%**	**78 days**	**Wed 9/19/18**	**Fri 1/25/19**		
66	L1			Milestone Report Writing	0%	11 days	Wed 9/19/18	Thu 10/4/18	58	70,69,67
67	L1		4	MS 4 Completion [Report]	0%	0 days	Thu 10/4/18	Thu 10/4/18	66	68
68				Margin	0%	26 days	Fri 10/5/18	Wed 11/14/18	67	69
69	L1		4	Promise date: MS #4: Reach TRL-5 [November 2018]	0%	0 days	Wed 11/14/18	Wed 11/14/18	66,68	72FS+21 day
70				Journal paper writing	0%	49 days	Fri 10/5/18	Thu 12/20/18	66	71
71	L2			Journal paper submission [December 2018]	0%	0 days	Thu 12/20/18	Thu 12/20/18	70	
72	L1			TAC Review [1 month after TRL-5: December 2018, TBC*]	0%	0 days	Tue 12/18/18	Tue 12/18/18	69FS+21 d	73
73				Address TAC feedback	0%	15 days	Wed 1/2/19	Fri 1/25/19	72	

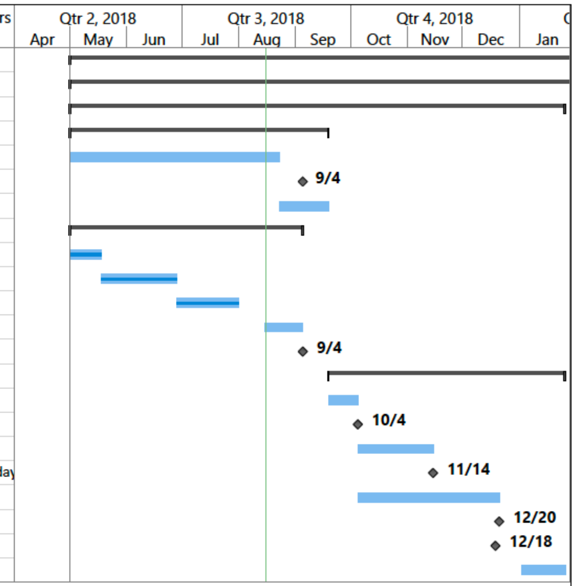

Table 7 shows the current risk list for the formation flying technology development activities. As the formation flying technology development is nearly complete, there is very little risk remaining. The only risk (low) is assigned to the possibility that the SLATE will be unavailable for any follow-up work that might be needed, due to another project occupying its laboratory space.

Table 7: Risk list for the formation flying technology development.

Risk ID	Risk Title	Likelihood (1-5)	Consequence (1-5)	Rating	Possible Mitigation
11	SLATE unavailable	1	3	Low	Hold on to lab space until after successful TAC milestone review

2.3 LARGE-STRUCTURE PRECISION DEPLOYMENT AND STABILITY

In making its trade study of mechanical architectures, S5 adopted several 'must-haves' and 'wants' for the mechanical technologies. The starshade must deploy accurately and reliably to the desired shape; and to that end, it is desirable that it use simpler and lower risk deployment actuations to provide high confidence in reliability, that it credibly shows at least 100% margin on derived deployment accuracy requirements, and that deployments and deployed performance be verifiable analytically using models validated by ground tests. The starshade mechanical design must also meet on-orbit shape stability and optical performance requirements (shape stability); and to that end, it is desirable that it show at least 100% margin on driving Technical Performance Metrics. The mechanical technologies must reach TRL4 prior to the Decadal Survey, with a compelling plan for reaching TRL5; and that it has high maturity and low risk in key hardware components and subassemblies. The mechanical technologies must have a credible and affordable path forward for TRL6. Finally, the mechanical architecture and technologies must credibly scale to future exoplanet missions; it is desirable that the range of allowable sizes be as large as possible, and that there be high flexibility of the mechanical design to accommodate multiple starshade shapes (e.g. apodization functions, numbers of petals).

The assumed funding profile is not sufficient to bring the starshade mechanical design to TRL5 prior to the deliberations of the Decadal Survey. The S5 plan for mechanical design therefore includes milestones to demonstrate TRL4 in time for the Decadal Survey as well as demonstrating the critical environments for each of the key performance architectures.

2.3.1 *MECHANICAL ARCHITECTURE DESCRIPTION*

A detailed description of the starshade mechanical architecture can be found in the HabEx flagship study interim report.[45] To provide context for understanding the technology development plan, we summarize it here.

The starshade is a passively controlled precision optical structure too large to fit within current launch vehicle fairing technology, and therefore requires an in-space deployment to achieve the requisite size and shape precision on-orbit. The function of the starshade mechanical system is to reliably deploy on orbit, and meet the required shape accuracy, stability, and solar glint requirements to meet mission performance. The baseline S5 architecture leveraged existing heritage deployable structure technology to formulate a concept that minimizes uncertainty in technology development and flight implementation. The approach allows the precision structure of the starshade mechanical

[45] *HabEx interim report.*

system to be functionally separated into two distinct subsystems, the petal and inner disk, that have separable requirements and can be developed in parallel, and validated with separate technology demonstrations. A separate integrated subsystem, the petal launch restraint and unfurl subsystem (PLUS), restrains and unfurls the petals through launch and on-orbit, respectively, and is then jettisoned. Figure 16 shows how these subsystems combine to form a complete starshade. Each subsystem further breaks down into two principal constituents, the mechanical structure and the optically opaque member, or optical shield. The deployment of the petals, and then truss, is both sequential and independent from each other via separate mechanisms, as shown in Figure 17.

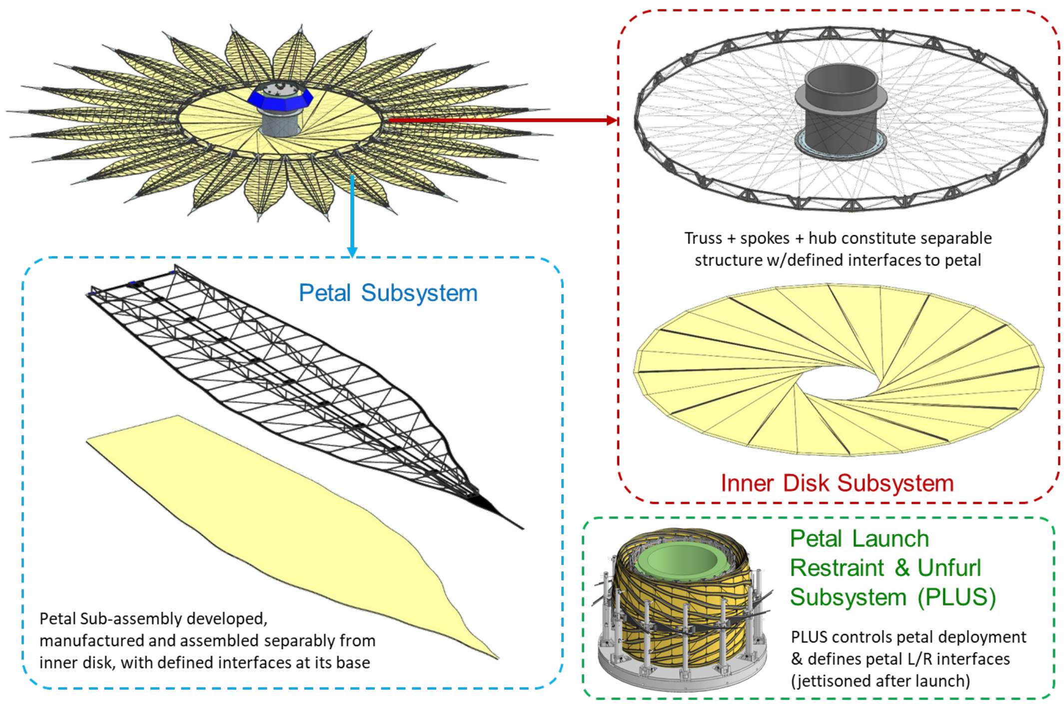

Figure 16: Major subsystems of the mechanical architecture.

The starshade inner disk is an adaptation of the Astromesh antenna perimeter truss, and is the core of the structure to which the petals attach. The Astromesh antenna is lightweight, precise and has a large deployed diameter to stowed diameter ratio, allowing for very large deployed diameters that fit within a small fairing. The Astromesh antenna has successfully deployed at least nine times on orbit, providing credibility to the deployment technology.

The addition of the petals to the circumference of the inner disk perimeter truss requires the petals furl, or wrap, in order to fit within the launch fairing. To deploy, the petals unfurl, illustrated in the unfurling portion of the deployment sequence in Figure 17. The S5 mechanical design wraps the petals using the Lockheed Martin Wrap-rib Antenna concept, in which the petals are spirally wrapped around the stowed perimeter truss and central spacecraft for launch. Wrap-rib Antennae have successfully deployed hundreds of times on orbit.

It is important to note that wrapping of the petals is in the out-of-plane direction, so as not to directly strain the in-plane shape of the petal, the critical dimension for petal performance. Unfurling the petals is accomplished quasi-statically with the PLUS, a separate "unfurl" mechanism, unlike the dynamically deployed wrap-rib antenna; the PLUS is not considered a technology gap, but rather an engineering development within the S5 plan necessary for understanding the interfaces required on the petal and as an environment the petals must be subjected to for TRL5 without contacting each other.

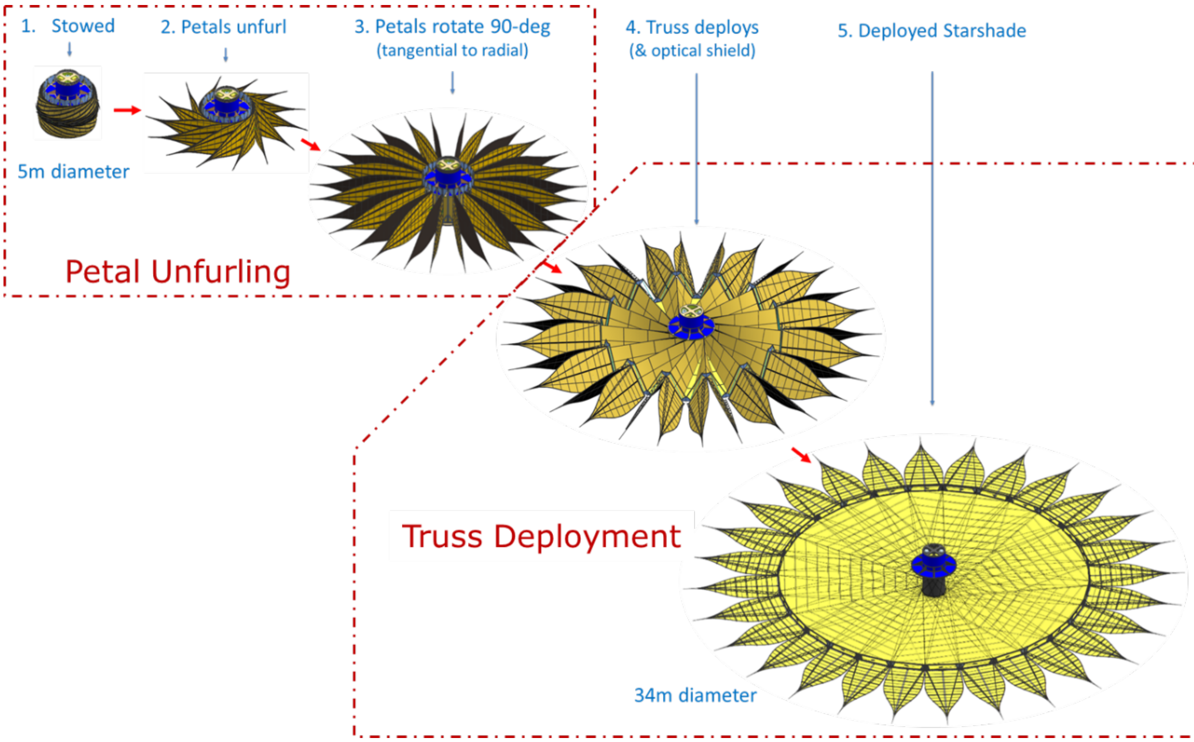

Figure 17: Deployment sequence of S5 starshade.

The PLUS is a large carousel assembly that rotates about the spacecraft hub long axis (Figure 18). For launch, the PLUS is locked in rotation, and the vertical cage posts around its perimeter serve as an external boundary condition that preloads radially-aligned launch restraint interfaces on the central spines of the spirally wrapped stack of petals. Two petal edge restraint features extend tangentially from the top and bottom of the vertical cage posts to control dynamic excitation of the petal edges during launch and also align with radially-oriented features on the petal battens, the width-wise members of the peal. Once on orbit, the petal preload mechanisms on the cage posts are released, at which point each petal is only lightly preloaded by its furled strain energy by the restraining roller assembly on the post that is centered vertically on the petal, aligning with the petal central spine. The carousel rotational constraint is then released, and a single, redundant motor system slowly and deterministically rotates the carousel with respect to the wrapped petals, allowing for controlled release of the petals furled strain energy and ensuring no damage to the petals' edges. Once the petals have fully unfurled, they passively rotate to a radial orientation in response to torsion springs in the hinges that attach them to the perimeter truss, with the roller assemblies continuing to provide restraint through the rotation. The vertical cage posts are then released to rotate radially down and out of the way of the petals/truss system, via a release mechanism and torsion spring, allowing for the entire PLUS subsystem to be jettisoned before truss deployment.

The perimeter truss, by virtue of its deployment, rotates the truss longerons, to which the petals are attached, from vertical to horizontal, thus rotating the petals into their radial and planar state through perimeter truss actuation only. The truss is composed of thermally stable carbon fiber composite tubes- 'longerons'- that form a perimeter ring that is placed in compression upon final deployment by the tensioned carbon fiber composite spokes that connect the ring to the central spacecraft hub. This stiffens and thus stabilizes the structure to which the petals attach (much like a bicycle wheel).

The entire disk is covered with an inner disk optical shield, consisting of multiple layers of carbon impregnated black kapton, a material that intrinsically meets the opacity requirements. Separation between the kapton layers mitigates the effect of micrometeoroid impacts by reducing the percentage of micrometeoroid puncture holes that will provide a direct path for starlight to enter the telescope. The inner disk optical shield fold lines are designed to spirally wrap with no stowed strain energy in the negative space between the perimeter truss and the hub in the stowed configuration.

The perimeter truss deployment is fundamentally the same as that successfully used in the Astromesh antenna: deployment is controlled by a motorized spool that reels in a braided steel cable that serpentines the truss diagonals, unfolding and expanding the perimeter truss. The deployment of the truss pulls out the spirally folded opaque optical shield. Upon deployment, the optical shield has no surface accuracy or in-plane profile requirements, just the opacity requirement.

The starshade petal is designed to be a thermally stable structure, which does not require the articulation of any joints or tensioned members to create its structure. Figure 19 shows its detailed construction. The petal is a thin and gossamer carbon fiber composite structure. As manufactured, the petal meets its in-plane shape requirements, most critically its width. The stability of the petal width is provided by thermally stable pultruded carbon fiber composite tubes- battens- that hold the petal structural edge. The optical edge is provided by discrete meter-long segments that are bonded to the structural edge at precise locations along its width and at the petal tip. The optical edge has the precise shape profile that provides the starlight suppression. The optical edge is manufactured from a thin strip of amorphous metal alloy, with a sharp bevel chemically etched into it that limits solar glint into the telescope (see the inlay in Figure 19). The entire petal is loosely covered with the same opaque optical shield material as covers the inner disk.

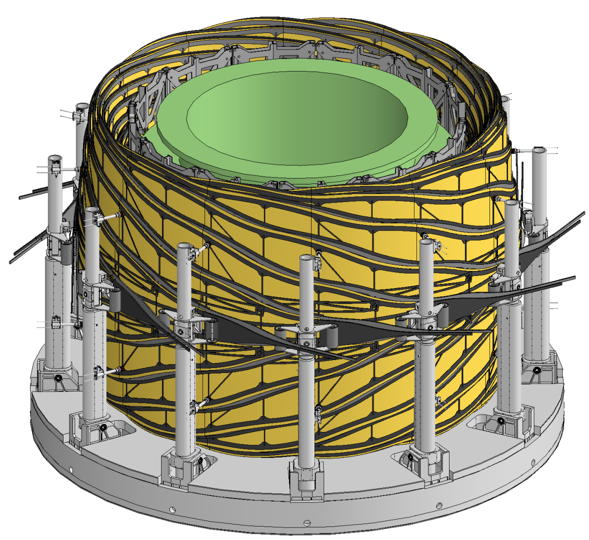

Figure 18: PLUS unfurler, shown in the stowed state.

The petals are made thin so that they can be wrapped for launch, but it is desirable that they be stiff after deployment. The out-of-plane stiffness of a deployed petal is provided via two ribs running the length of the petal that attach near its base to the perimeter truss at a distance from the petal plane. These ribs are piano-hinged on the petal and passively deploy via reliable and redundant over-center sprung hinges.

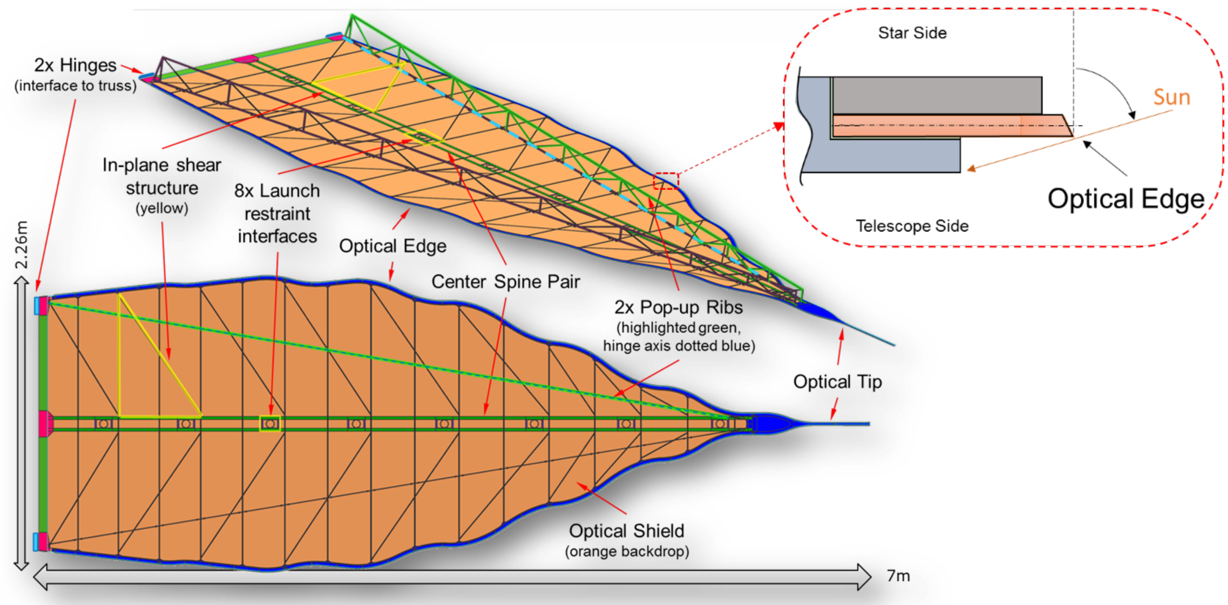

Figure 19: Detail of starshade petal, including cross section of optical edge.

In concluding that ground-based testing was sufficient to bring starshade technology to TRL6, the SSWG noted that ground tests of high-fidelity full-scale prototypes can fully verify deployment. Ambient deployments tests with negligible air drag and imperfect gravity compensation conservatively envelope the space vacuum and 0-g environments. High deployed stiffness enables gravity compensation of manageable complexity. Thermo-vac tests of high-fidelity full-scale assemblies (e.g. petals and inner disk truss) fully validate thermal models. Vibration tests of a full-scale stowed system fully validate structural models.[46] They also noted that laser metrology and precision photogrammetry can fully verify the deployed shape, and that Structural Thermal Optical Performance (STOP) analysis with validated models can verify on-orbit stability. Finally, they noted that ground-based verification is standard practice for large deployable structures within the aerospace industry. The S5 plan to develop petal shape and deployment technologies to TRL5 applies all these methods, the only difference being that in some cases half-scale prototypes are tested.

2.3.2 *MECHANICAL KEY PERFORMANCE PARAMETERS*

The error budget described in section 2.1.4 has been used to allocate the allowable contrast error due to departures from the ideal starshade shape down to tolerance requirements for the overall

[46] *"Starshade Readiness Working Group Recommendation to Astrophysics Division Director", G. Blackwood, S. Seager, N. Siegler, and T. Hyde, November 9, 2016, page 47.*

starshade shape. These have been broken down into tolerances on the petal shape and petal position, and each of these further broken down roughly into pre-launch tolerances and tolerances on in-flight thermal stability. These four tolerances are the mechanical Key Performance Parameters 5-8 in Table 1; KPP5 and KPP6 together bring the petal shape and stability technology S-4 to TRL5, and KPP7 and KPP8 together bring the petal position accuracy technology S-5 to TRL5. The following sections detail the plan that brings the starshade mechanical technologies S-4 and S-5 to TRL5, within the context of mechanical architecture described above. Figure 20 shows a summary of the key activities and articles within that plan. Figure 21 shows a summary schedule for the mechanical technology development and engineering activities.

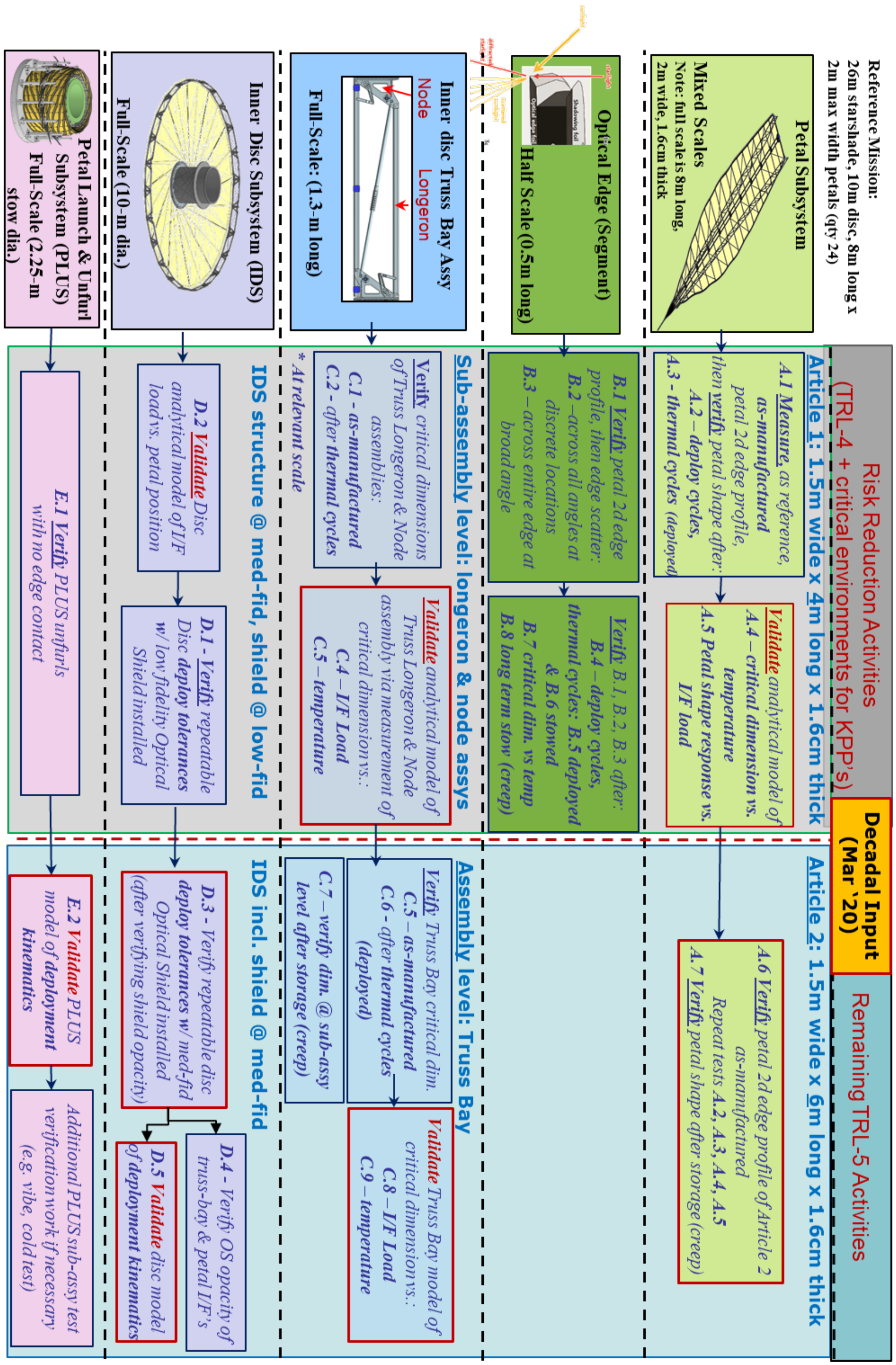

Figure 20: Top-level summary of key activities that bring the starshade mechanical technologies to TRL5.

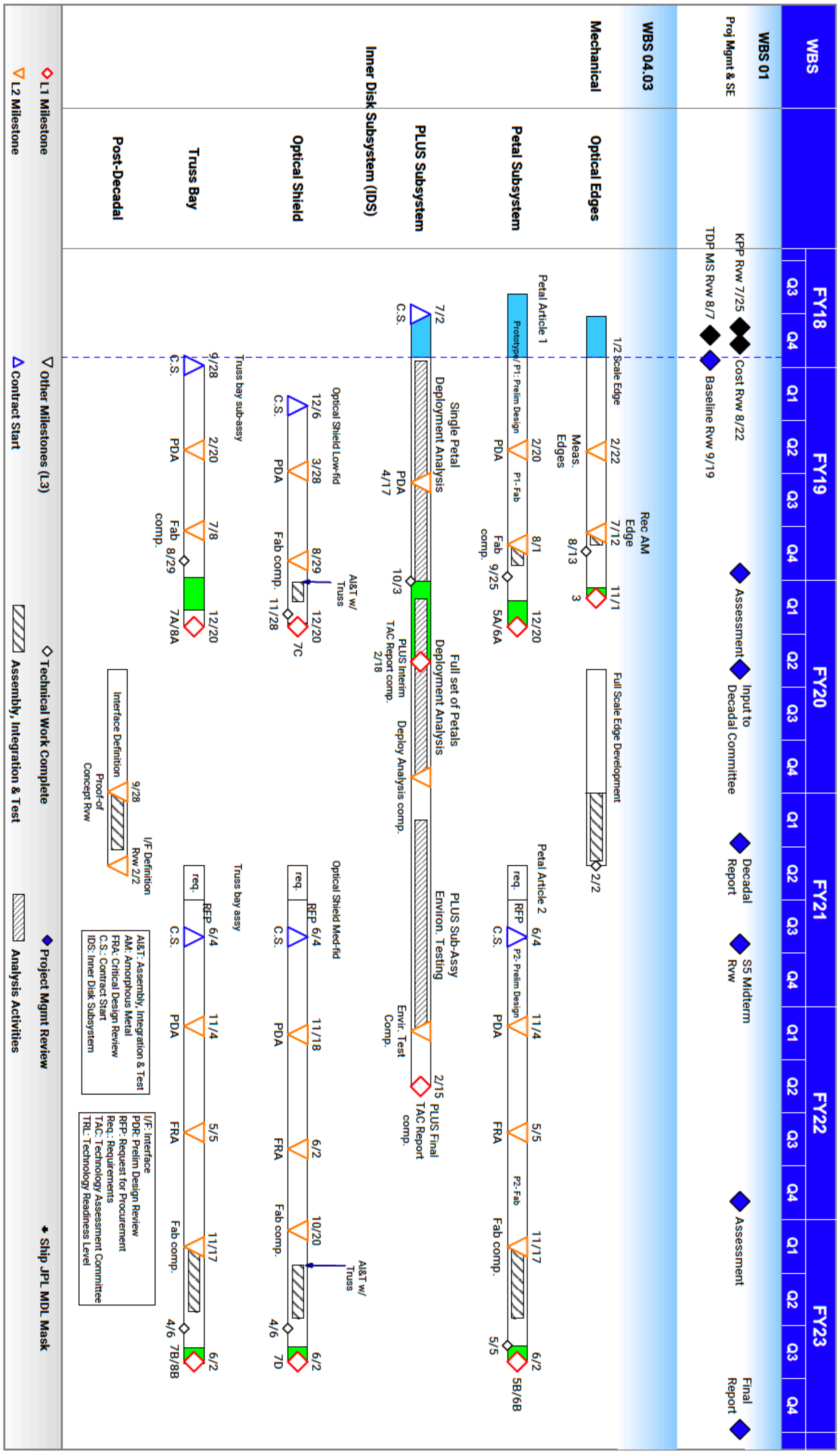

Figure 21: Top level schedule for starshade mechanical development.

2.3.3 *PETAL POSITION ACCURACY AND STABILITY (S-5)*

2.3.3.1 Truss Bay

Figure 22 shows the truss bay assembly.

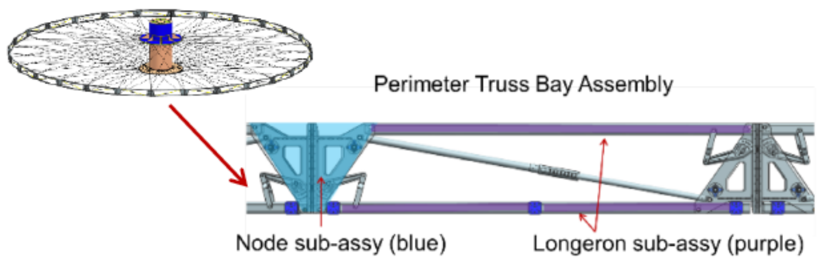

Figure 22: Truss bay assembly, showing its location within inner disk and locations of longeron and node subassemblies.

The first test of the inner disk truss bay will be to assemble longeron and node subassemblies and measure their critical dimensions as built. The 'critical' dimensions within the truss bay are those that determine the petal position. The subassemblies will then undergo several thermal cycles over the mission observing temperature range, and upon return to room temperature be remeasured to verify dimensional change is within a level consistent with pre-launch position accuracy within 300 microns. The measurements would be made using a MicroVu Excel 250 CMM accurate to roughly 10 microns. The longeron and node subassemblies themselves will be of ½ scale or greater and of medium fidelity, and will include all features that significantly contribute to thermal cycle induced petal position error. Successful completion of this test is top-level milestone 7A towards demonstrating KPP7. It is scheduled to be completed 12/20/2019 in order to inform the Decadal Survey.

The subassembly will then undergo stress/strain testing to measure effective elastic moduli of the assemblies and verify shape stability before and after load (using outside vendors or in-house setup if more practical). There will also be measurement of critical dimensions of the subassembly as a function of temperature over the full observing temperature range (this would be done at commercial vendors). These tests validate models of the subassembly response to temperature and load. Successful completion of this activity is top-level milestone 8A towards demonstrating KPP8. It is scheduled to be completed 12/20/2019 in order to inform the Decadal Survey.

The next test will be of creep of a longeron during the stowed stresses from initial storage until deployment on orbit. The longeron subassembly will be subjected to simulated loading, temperature and time comparable to that seen in a mission, and then the critical dimensions will be remeasured using standard metrology.

The next tests deal with longerons and nodes combined into a full-scale truss bay assembly. This article will be of medium fidelity, and will include all features required to interface to the petal and for launch restraint. The first such test, like that for the truss bay subassemblies, measures the critical dimensions of the as-manufactured truss bay assembly and verifies it is within the loose tolerance required at this stage, and serves as a reference for following tests. The truss bay will then be thermally cycled and remeasured for any resultant dimensional change. It will then be subjected to stowed stresses using an interface load simulator, and its critical dimensions measured to validate a model of critical dimensions of the truss bay assembly vs interface loads. The interface load simulator will be purchased from a commercial vendor. Successful completion of these tests is top-level milestone 7B towards demonstrating KPP7, and is scheduled to be completed 6/2/2023. Lastly, a model of critical truss bay dimension change vs temperature will be validated to within 200 microns using standard metrology in a hot box over the full operating temperature range, similar to the thermal deformation testing of the SWOT EM truss at NGAS San Diego facility, which can achieve 2 micron accuracy over a sufficiently large temperature range for the starshade. Successful completion of this final test of thermal stability is top-level milestone 8B, and finally demonstrates KPP8. It is scheduled to be completed 6/2/2023.

2.3.3.2 Inner Disk Subsystem

The inner disk's perimeter truss must reliably deploy to its final circular shape with precise dimensional tolerances. The optical shield within the perimeter truss must also deploy reliably, in that it does not impact the truss deployed shape tolerance or the reliability of the truss deployment, or that of the petals. It must also reliably deploy to be opaque. A full-scale inner disk article will be manufactured.

The KPPs as applied to the truss are that it deploy to the correct dimensions and that its dimensions be stable during operation. To this end, we will test a full inner disk system comprising the hub, spokes and optical shield in a 1-g lab environment, and verify the petal position accuracy by measuring the positions of the petal interface points. To verify petal position stability, we will validate the inner disk structural model (including using data from the truss bay tests). Thermal stability inputs to the inner disk model not arising from the truss bay (i.e. from spokes) will be verified at the subassembly level. All tests will be at full scale.

The first test will verify repeatable disk deploy tolerances with a low fidelity optical shield. The low fidelity optical shield will use low fidelity components and assembly, but include deployment critical features and consist of flight-like materials (e.g. Kapton). The remaining components (perimeter truss and spokes) will be at medium fidelity. This test will be done in the JPL starshade lab or a similar facility, using laser trackers for metrology to within 25-50 microns. This test exit criteria will be to meet the 300 micron tolerance for petal position at the petal interface points. Successful completion of this inner disk deployed shape test is top-level milestone 7C towards demonstrating KPP7. It is scheduled to be completed 12/20/2019. The conclusion of this testing will constitute TRL-4 for the inner disk subsystem including the optical shield. As part of the development process, the opacity of representative sections the multilayer shield will be measured.

The next test will validate a structural model of inner disk stiffness by applying known loads and measuring responses on the first inner disk article. This will use the same metrology, with known external loads applied to the truss bays and petal position movement measured.

S5 will then construct a full-scale, fully medium fidelity second inner disk article similar to the first article except with a medium fidelity optical shield meeting TRL5 requirements. The inner disk assembly will also include will include four 4x6m length petals, and remaining truss bays populated with petal base units only, to enable assessment of petal interface loads on truss deployment accuracy and reliability. The opacity of the interface between the inner disk and the petals will be verified on at this time, most likely at a test article level of assembly. Lab deployment of this article will validate the model of deployment kinematics, by measuring the shape as a function of deployment, and deploying and retarding forces. Finally, the deployed shape of the second article will be measured to verify that the petal position accuracy is within 300 microns. Successful completion of this second inner disk deployed shape test is top-level milestone 7D, and finally demonstrates KPP7. It is scheduled to be completed 6/2/2023.

Milestones 7B, 7D and 8B together demonstrate that the petal position accuracy and stability technology S-5 is at TRL5.

2.3.3.3 Petal Launch restraint and Unfurl Subsystem (PLUS)

The PLUS serves the purpose of restraining the petals during launch, and then unfurling them on orbit, and must do so without altering the deployed petal shape and edge scatter performance. The following engineering work and tests will be performed within the S5 technology development plan as an essential part of the mechanical architecture concept.

The PLUS test article is a medium fidelity, full-scale test unit, with a full complement of 24 petal and roller assemblies. The first test will verify that the PLUS can unfurl the petals with no edges contacting any other part of the starshade or its deployment system. The verification of no edge contact will be performed on only one pair of medium fidelity petals. The surrounding two pairs of petals will be of lower fidelity, but have the essential features that potentially interface with the tested petals. The remaining 18 petals will be of lower fidelity. The petals will be full width and thickness, but foreshortened to 6 meters length to fit into the Tendeg test bay. The stowed curvature will be the same as for a full-scale petal. Early environmental tests of critical subassemblies may be performed as needed to define the PLUS subsystem (e.g. vibration testing).

Another test will validate a model of petal kinematics during PLUS deployment. S5 will develop a flexible body kinematic model of the petal unfurling, including the PLUS as a boundary condition. Measurement variables and methods are TBD.

2.3.4 *PETAL SHAPE ACCURACY AND STABILITY (S-4)*

Full-scale petal prototypes have already been built that show shape accuracy is sufficient to meet contrast requirements.[47] This test demonstrated TRL4 for the petal shape, by demonstrating shape accuracy in a laboratory environment. Figure 23 shows a full-scale petal of an early design that was assembled and measured using a CMM probe, along with the measured variances from the nominal shape. The grey bands show the acceptable tolerance bands as they were understood at that time for 10^{-10} imaging. The current error budget includes a more detailed understanding of allowable error spatial scales, that with direct optical modeling of the measured profile shows that it already meets contrast requirements, and thus because this demonstration constitutes higher confidence in our capabilities, we have reduced the margin on this error budget area.

[47] *"Advancing Technology for Starlight Suppression via an External Occulter'" N. Jeremy Kasdin. TDEM-9 final report.*

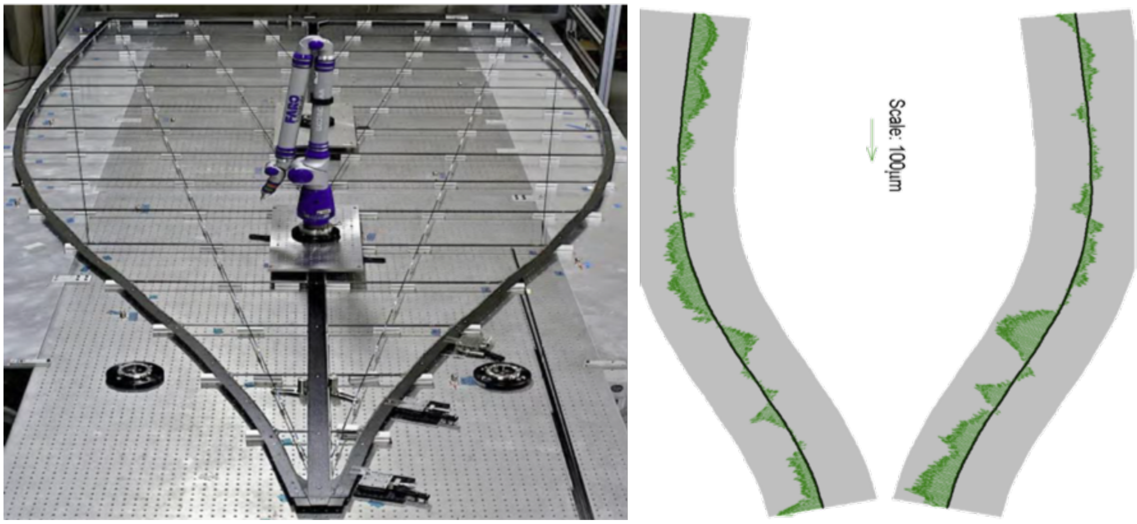

Figure 23: Left: prototype petal from TDEM-9. Right: measured errors from nominal shape (green) and bounding envelope meeting suppression requirements (grey).

The manufacture of this petal was of low fidelity relative to the expected launch design in that it did not include sharp edges for reduced glint, all features and interfaces or an optical shield. The S5 test plan is to complete two further design cycles of the petal, with test results from the as-built prototype units of the first cycle informing the second design cycle. Article 1 will focus on dimensional stability of the structure with flight-like materials, but with reduced fidelity of the interfaces to other assemblies. It will not include subassemblies that by design do not influence petal shape (e.g. petal optical shield). Article 2 will be medium fidelity: all subassemblies and interfaces at medium fidelity. The edge segments and tips for article 2 will also meet the manufactured shape and edge scatter requirements. Engineering work during these cycles will include characterizing the CTE of critical components, joints and subassemblies within the petal assembly. The S5 prototype petals will be ¾ scale in width (the critical dimension), to fit into the existing Micro-Vu CMM, and full thickness (not a critical dimension for optical performance, but this choice matches the elastic performance of the test article to that of a flight article) and allows for selection of the proper flight component materials. It will also be half-length, to fit into an existing thermal metrology facility (length is not critical dimension). This foreshortened petal has the same behavior as a full-sized petal in terms of critical performance parameters. The edge segments and tips will be full width, but half length. Thus, the prototype shape will differ from that of a full petal, but this does not impact the model validation.

The first test step will be to measure the as-built edge profile (shape) of the installed edge segments and tip shape of petal article 1 for the purpose of establishing a manufactured reference shape. These edge and tip segments are not meant to demonstrate correct shape or scatter performance, but only to demonstrate/evaluate dimensional stability after manufacture after having been exposed to environments. The petal edge profile will be measured using an Excel-250 Micro-Vu automated precision measurement system. A smaller version of the Micro-Vu, the Excel-1051, is shown in Figure 24 in the starshade lab at JPL. The Micro-Vu has an accuracy of ~10 microns over the 1.6m wide by 2.5m long measurement bed. Because the bed is shorter than the petal length (2.5m bed compared to 4m petal length), this measurement setup shown in Figure 25, involves bookending the Micro-Vu with optical benches to support the petals where they overhang. The petal will be measured in overlapping sections of this length, and the edge shape stitched together using software already developed for this purpose. Because petal surface stiction can alter the in-plane shape, analysis and design will be implemented to reduce surface stiction to acceptable levels for the repeatability and accuracy of the petal shape measurement. One concept developed to achieve this is for the petal to ride on plastic beads on the Micro-Vu and rollers on the benches as it is pushed through the scanner, which is the concept shown in the figure. This measurement provides a reference for the ensuing tests. All subsequent measurements post-environment, will be measured in the same fashion, and then compared against the reference measurement. Note that the baseline measurement will likely include several measurements to understand the variability (repeatability) of the petal structure as-measured on the Micro-Vu.

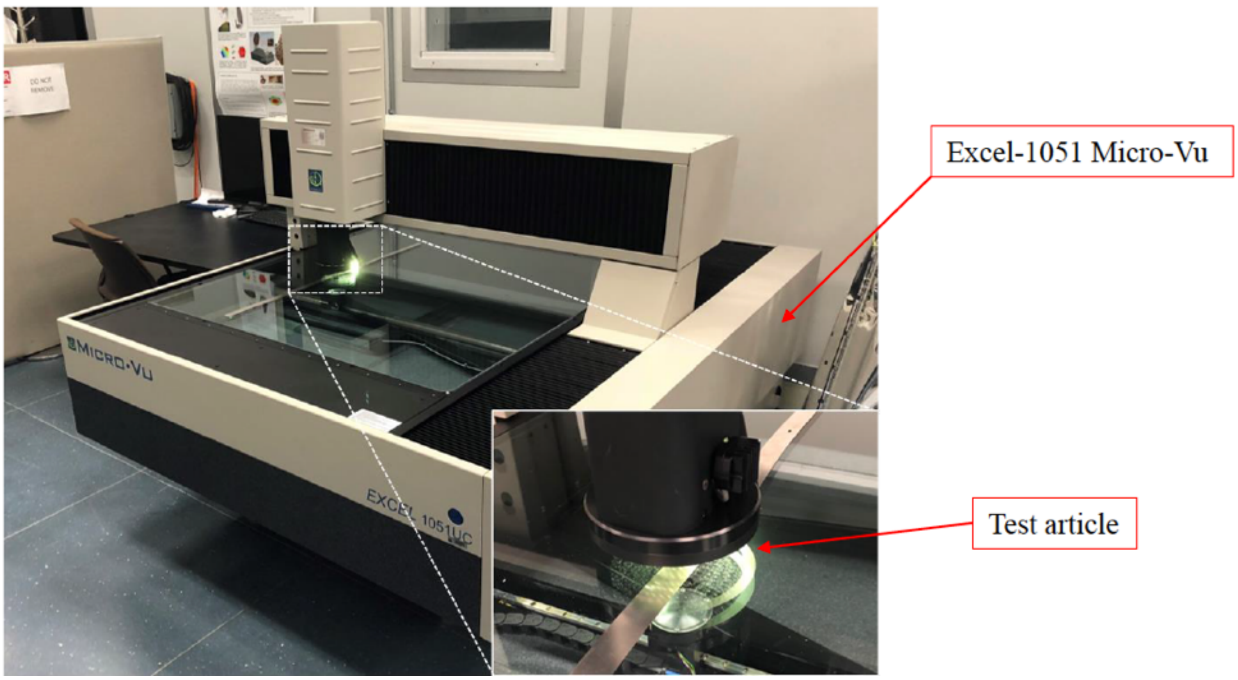

Figure 24: Excel-1051 Micro-Vu measurement system.

The next test will be to verify shape stability after a set of deployment cycles that are statistically relevant to bound the expected errors from a relevant number of deploy cycles that is based in the expected deployment for the flight article, which will likely deploy between five and ten times between ground tests and the in-flight deployment. To achieve the deploy cycles, the petals will be furled and unfurled on a hub simulator that matches the stowed curvature (Figure 26). The petals will be then be re-measured and compared against the as-manufactured reference petal shape using the Micro-Vu Excel-250. The petal shall be within acceptable shape error tolerance if it is within 70 microns of initial shape. Only shape deformations that change the width profile of the petal as a whole, along in-plane directions, are considered significant for these tests. (See section 2.1.4 for further explanation.)

The next test will be to verify the shape stability of the article 1 petal after thermal cycling. As with the test for the truss bay, the thermal cycling will reproduce that seen by the petal during the mission observations, though this may differ from the range seen by the truss. The assembled petal shall be within acceptable tolerance if it is within 70 microns of the original in-plane shape. Successful completion of these petal shape tests against deployment and thermal cycles is top-level milestone 5A towards demonstrating KPP5. It is scheduled to be completed 12/20/2019.

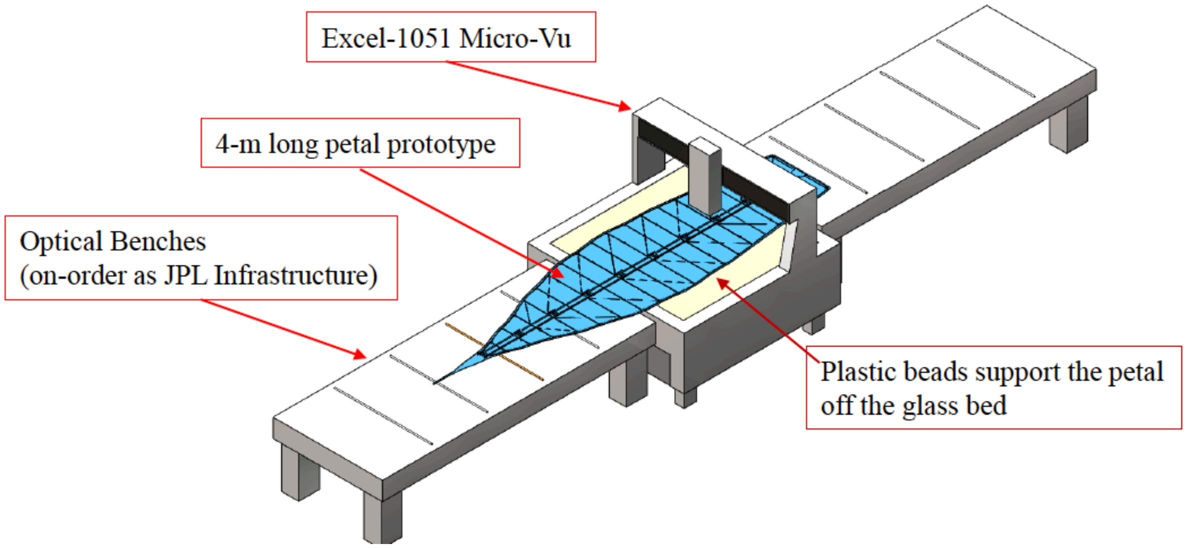

Figure 25: Layout of shape metrology for half-scale petal article (test B3).

Petal article 1 will then be used to validate a model of the change with temperature of width (the critical dimension) of the petal at multiple points along the petal edge. This will be done using laser interferometry in a hot/cold box, a standard aerospace metrology method also used for the SWOT and JWST missions. Temperatures will span a relevant temperature range sufficient to validate the model of deformation across the observing temperature range. This is the same method that will be used to test thermal shape change of the truss bay, and will have the same 2-micron accuracy. The test will be successful if the petal shape demonstrates flight stability to within 80 microns. Successful completion of this test is top-level milestone 6A towards demonstrating KPP6. It is scheduled to be completed 12/20/2019.

S5 will then fabricate the second petal (article 2), which in addition to its higher fidelity and ¾ scale length, will incorporate any design changes motivated by other S5 activities by that time. A significant difference between petal article 2 and its predecessor, is that article 2 will be measured and verified to that it meets the manufactured edge profile shape requirements. Additionally, article 2 will be verified to meet the solar scatter requirements (glint) requirements. This article will also be subjected to the same set of tests of critical dimension stability against thermal and deploy cycles as in milestone 5A for the first petal article. It will also be subjected to a test of creep during stowed storage, with the I/F forces in the stowed state mimicked using a jig, and the appropriate location on the temperature/time dependence curve to simulate the storage of the flight unit first stowed on the ground (3 years) through deployment in space (two months). Successful completion of these tests is top-level milestone 5B, and demonstrates KPP5. It is scheduled to be completed 6/2/2023.

Petal article 2 will also be used to validate a model of the petal shape change against I/F forces.

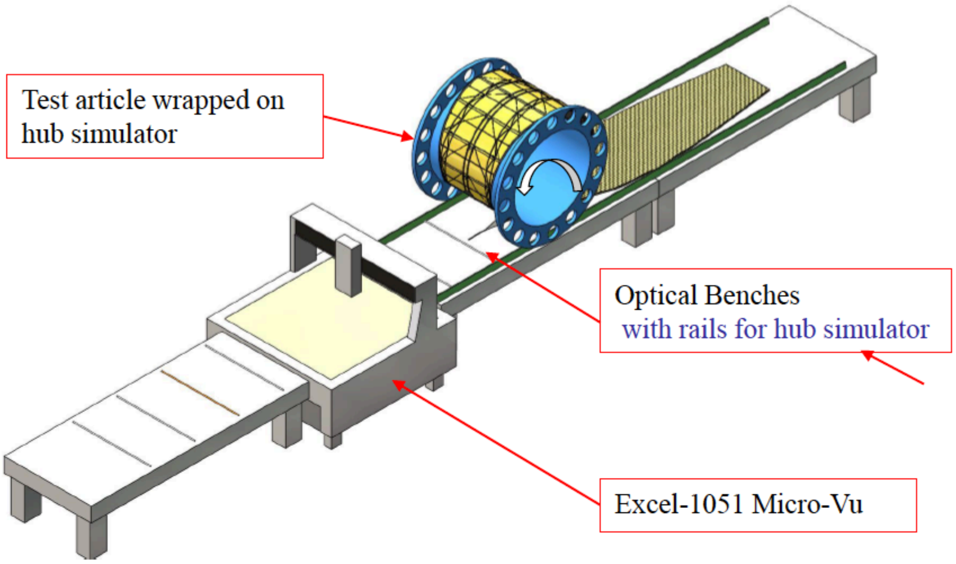

Figure 26: Layout of petal furling test B2.

The final test of petal article 2 will validate a model of petal and truss bay shape change vs. temperature. This test will be fundamentally the same as the test of petal article 1 in milestone 6A. Successful completion of this test is top-level milestone 6B, and demonstrates KPP6. It is scheduled to be completed 6/2/2023.

Milestones 5B and 6B together demonstrate that the petal shape and stability technology S-4 is at TRL5.

2.3.5 *OPTICAL SHIELD PERFORMANCE*

The opacity of the optical shield will be tested at specific locations to verify that leaked or scattered sunlight internal to the edges will not exceed the requirements shown in Figure 2. The specific locations to be tested are still TBD but are likely to include the petal/truss interface and any locations where through holes in the optical shield for mechanical access are covered by flaps, as well as artificially induced micrometeoroid holes in various locations. Reducing this stray light to within requirements is seen as an engineering effort and not technology development. The opacity testing may be done at the NGAS opacity testbed or internally at JPL. This activity will occur in the period following the report to the Decadal Survey.

2.3.6 *MECHANICAL TECHNOLOGY DEVELOPMENT RISKS*

The currently identified risks for starshade mechanical development are listed in Table 8.

Table 8: Risk list for the formation flying technology development.

Risk ID	Risk Title	Likelihood (1-5)	Consequence (1-5)	Rating	Possible Mitigation
13	SBIR contractor cannot deliver spokes	3	2	Med	Use current low-fidelity spokes in medium-fidelity article. Buy higher cost articles outside of SBIR contract.
17	PLUS deployment modeling too complex	2	2	Low	

2.4 SUMMARY OF TRL 5 SUCCESS CRITERIA AND MILESTONES

Table 9 summarizes the milestones and exit criteria, showing which milestones are met prior to the Decadal Survey and how much of the technical risk they retire by that time.

Table 9: Summary of S5 milestones.

MS #	Milestone	Report Completion Date	Exo-TAC Confirm by Decadal	% Risk Retired by Decadal
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.	1/28/19	X	100
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 the Fresnel number $\leq$ 15 at the longest wavelength.	3/30/19	X	100
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}.	1/15/20	X	100
3	Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.	11/1/19	X	100
4	Starshade Lateral Alignment Testbed validates sensor model by demonstrating lateral offset position accuracy to flight equivalent of $\pm$ 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within $\pm$ 1 m.	11/14/18	X	100
5A	Petal subsystem with *shape critical features* demonstrates shape stability after deploy cycles (deployed) consistent with a total pre-launch shape accuracy within $\pm$ 70 μm.	12/20/19	X	80
5B	Petal subsystem with *all features* demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, and storage) to within $\pm$ 70 μm.	6/2/23		
6A	Petal subsystem with *shape critical features* demonstrates on-orbit thermal stability within $\pm$ 80 μm by analysis using a validated model of critical dimension vs. temperature.	12/20/19	X	80
6B	Petal subsystem all *features* demonstrates on-orbit thermal stability within $\pm$ 80 μm by analysis using a validated model of critical dimension vs. temperature.	6/2/23		
7A	Truss Bay *longeron and node subassemblies* demonstrate dimensional stability with thermal cycles (deployed) consistent with a total pre-launch petal position accuracy within $\pm$ 300 μm. (Note: SBIR funding dependency)	12/20/19	X	80
7B	Truss Bay *assembly* demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within $\pm$ 300 μm.	6/2/23		
7C	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 $\pm$ 300 μm. (Note: SBIR funding dependency)	12/20/19	X	80
7D	Inner Disk Subsystem with optical shield assembly that includes *all features* demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within $\pm$ 300 μm.	6/2/23		
8A	Truss Bay *longeron and node subassemblies* demonstrate on-orbit thermal stability within $\pm$ 200 μm by analysis using a validated model of critical dimension vs. temperature.	12/20/19	X	80
8B	Truss Bay *assembly* demonstrates on-orbit thermal stability within $\pm$ 200 μm by analysis using a validated model of critical dimension vs. temperature.	6/2/23		

3 MANAGEMENT APPROACH

The S5 Technology Development Activity was initiated within the Exoplanet Exploration Program by the Astrophysics Division Director in a memorandum in 2016.[48] Per the ExEP Charter, programmatic direction "flows from APD to the ExEP Manager and from there to ….projects within the assigned program scope". The S5 task, as an element of the ExEP program, is led by a Technology Manager who is appointed by the Exoplanet Exploration Program Manager and the appropriate JPL technical division. Because S5 is implemented in a "mixed mode" (some elements in house at JPL and some at partners/subcontractors), the S5 task follows JPL management practices to ensure insight and oversight of the implementation and execution to ensure that it is implemented and operates in an efficient and effective manner consistent with JPL institutional policies, procedures and requirements.

3.1 ORGANIZATION AND WORK BREAKDOWN STRUCTURE (WBS)

Internal to S5, the activity is organized by technical discipline focus, with a lead engineer for each area. Figure 27 shows the organizational structure internal to the S5 task. Business team support is provided by the ExEP Business office personnel.

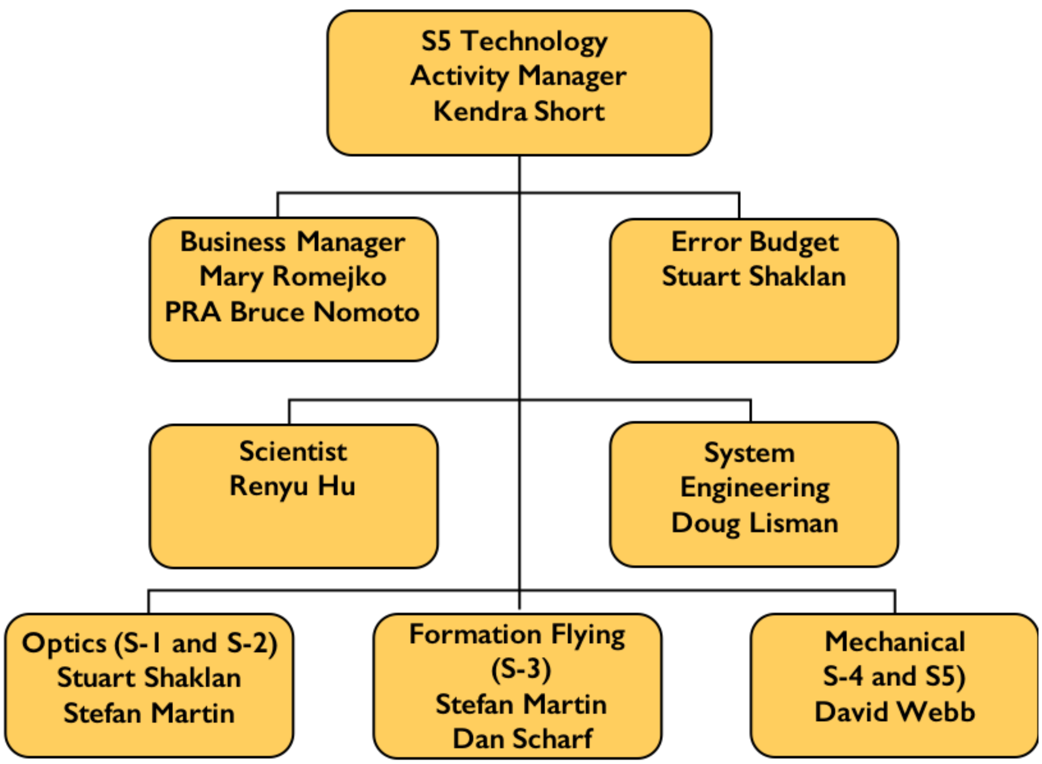

Figure 27: Organization chart for the S5 technology development activity.

The Work Breakdown Structure is derived from the standard WBS for technology projects provided in Appendix K of 7120.8. The current structure for the associated cost accounts for the S5 activity is shown in Table 10. Table 11 contains the dictionary of WBS elements. S5 expects that additional

[48] *"Starshade TRL-5 Preliminary Development Plan", Paul Hertz, 3-23-2016.*

subaccounts will be added as needed to plan and track major elements of the work. For example, in the time frame following the report to the Decadal Survey, development of each mechanical prototype article will likely be captured within a separate major subaccount.

Table 10: S5 Baseline Work Breakdown Structure

WBS	Title
01	Project Management
01.01	Project Management and System Engineering
01.02	Science and Industry Partnerships
04	Technology Development
04.01	Formation Flying
04.02	Optical Engineering
04.03	Mechanical Engineering

S5 includes activities within its management element to focus on partnerships and engagement with the science community in order to continually consider new ideas and have opportunities for new participants in starshade development, from both industry and academia. S5 will seek partnerships with industry by creating cost-sharing opportunities in areas of direct relevance to the S5 activities and focused on looking for new solutions to S5 objectives and challenges. S5 will create a Science and Technology Working Group (STWG) with academia that will keep S5 current on emerging science needs and provide reviews and potential solutions to difficult technology problems. This "forum" of the STWG and interested industry participants and NASA centers will convene once or twice per year to hear updates and reports from the S5 team as well as bring forth new information and ideas for consideration by the starshade team. The S5 team will include a part-time scientist to act as a liaison between the SWG, the S5 team and the ExEP Program Office.

Table 11: S5 WBS Dictionary.

WBS Element	Element Description
01 Project Management	
Project Management and System Engineering (01.01)	Provide day-to-day leadership and oversight of all work in the Activity. Develop qualitative and quantitative understanding of key technical issues and drivers, including current limitations and challenges. Determine the flowdown of requirements from the key science parameters down to subsystems and assemblies within the starshade and its interfaces. Allocate tolerances between subsystems. Provide business team support to the elements within S5 for budget, schedule and cost planning, tracking and reporting.
Science and Industry Partnerships (01.02)	Solicit guidance and feedback from exoplanet scientific community. Solicit new ideas in starshade technology development from industry through cost-sharing agreements and from academia through the STWG.
04 Technology Development	
Formation Flying (04.01)	Perform testbed measurement of lateral sensing capabilities. Generate models and simulations of the formation flying lateral control performance. Manage the SLATE testbed facility.
Optical Engineering (04.02)	Verify models of starshade optical performance and sensitivity to errors via optical testbed measurements. Development of scatterometer for edge scatter measurement.
Mechanical Engineering (04.03)	Development and test of mechanical articles, including petal article, optical edge subassembly, truss bay subassemblies and assembly, inner disk system, and PLUS.

3.2 COMPLETE SET OF TASKS, MILESTONES, AND SCHEDULE

Figure 28 shows the top-level summary schedule for all starshade technology development activities within S5. This top-level schedule is derived from a more detailed "integrated master schedule" (IMS) that contain the detailed implementation tasks for each technology area within S5. The IMS will be statused each month as part of the standard monthly management reporting.

A summary of the Level 1 key technology milestones in this Plan was shown in Table 9. S5 will also track a set of Level 2 milestones to monitor progress at intermediate steps in the technology and engineering development. The L2 milestones status will be reported monthly to the ExEP program manager. The S5 Activity will hold two assessment reviews and one midterm review during its planned execution. The two assessment reviews (to be held nominally 8/15/2019 and 8/15/2022) are for the explicit purpose of re-assessing S5's Key Performance Parameters and milestones in the light of any new scientific knowledge concerning starshades and their application to exoplanet imaging and characterization or any evolution in the mission concept needs. The midterm review will include an assessment of how the Decadal Survey report impacts the S5 plan.

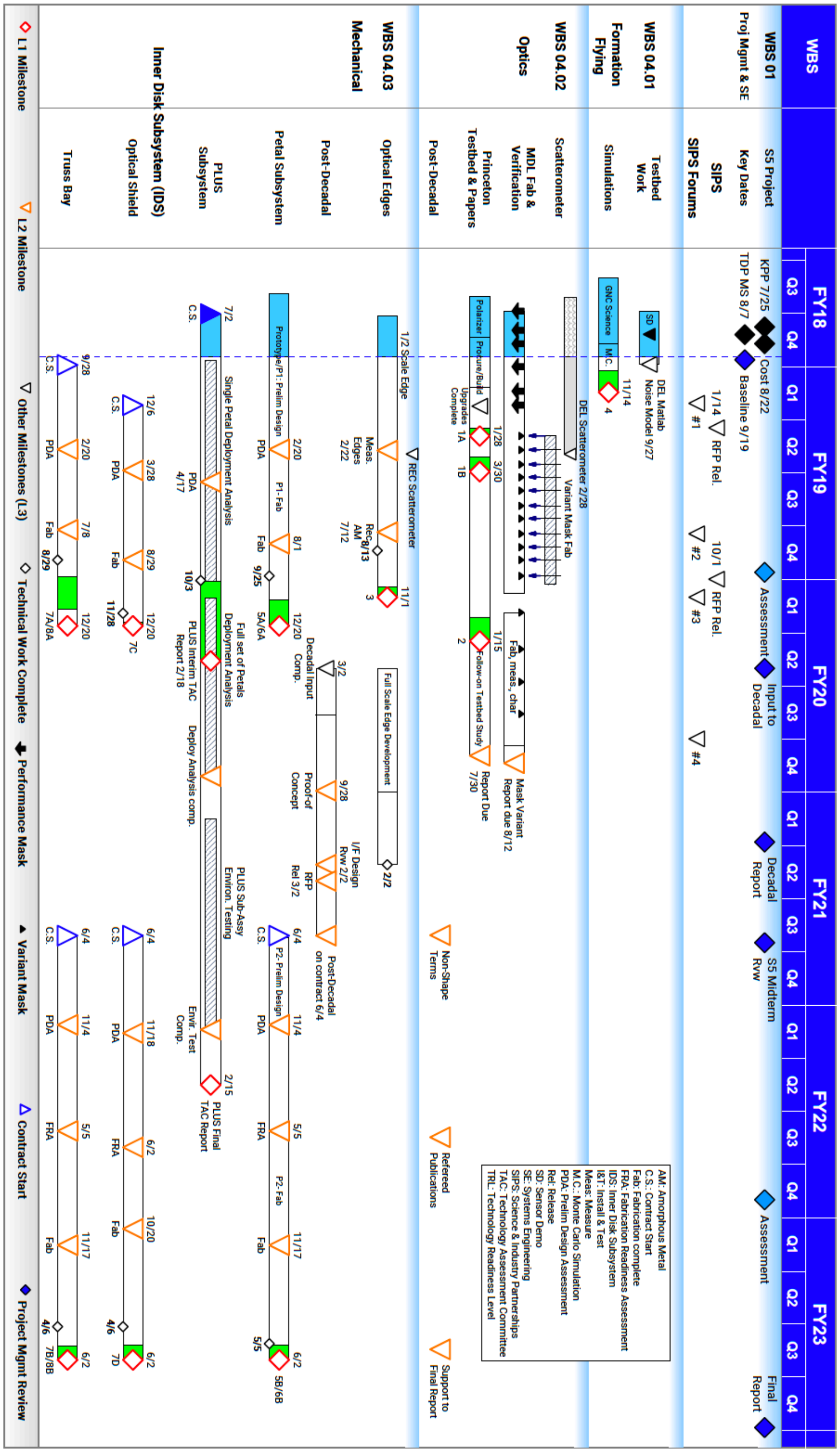

Figure 28: Top level schedule for all starshade technology development.

3.3 COST BY WBS AND FISCAL YEAR

The budget for S5 is shown in Table 12. This budget works to the assumed funding profile shown in Table 2; should the funding profile change, the plan will change its schedule and scope commensurately.

Table 12: Estimated Budget for S5

Starshade Life Cycle Obligation Profile	Prior	FY18	FY19	FY20	FY21	FY22	FY23	Total
[redacted]								

The workforce summary for S5 is shown in Table 13.

Table 13: Workforce Summary for S5

Task	Employee Name	FY19 Total	FY20 Total	FY21 Total	FY22 Total	FY23 Total
[redacted]						

3.4 RISK MANAGEMENT

The S5 activity will operate consistent with the ExEP Risk Management Plan (section 3.3 of the ExEP Plan). Even though the ExEP Risk Management plan is currently written for more formal projects, the S5 activity will follow the same process. The ExEP Risk Management Plan states that ExEP projects are required to:

1. Maintain a risk list
2. Develop mitigation plans for all red and all yellow technical and safety risks.
3. Monitor risks on a monthly basis.
4. Status risks with the Program on a quarterly basis. Projects will status all red and yellow risks. Status reports must include current estimates of risk likelihood, impact and trend.

The S5 activity will monitor and status its risks on a monthly schedule, as a recurring task within its management reviews. The primary risk management resources for S5 are schedule and scope definition, as well as adjustments to performance requirements through utilization of technical margins. The risk matrix will be maintained by the S5 Project Manager or their delegate, with input from the technology task leads and system engineer. Realized risks nominally will be reported to the S5 Project Manager as soon as they are known to occur, and no later than at the earliest following weekly meeting.

S5 will use JPL's web-based risk management tool to maintain a record of identified risks and of their mitigation, realization, or retirement. This risk management tool evaluates and ranks risks using a 5x5 matrix of likelihood and consequence ratings. S5 uses the definitions of the consequence ratings contained in the risk tool for the four categories of risk: these are shown for reference in Section 4.3 of this document. The risk tool ranks likelihoods from 1, 'Very Low', through 5, 'Very High'. In an attempt to roughly quantify these terms, S5 adopts the likelihood definitions given in Section 4.3 of this document. The likelihood definitions are common to all risk categories. Table 14 summarizes the likelihood/consequence ratings for the risks being tracked by S5 at this time. Table 15 gives descriptions of the risks and their possible mitigations. More detailed descriptions of the risk (e.g. If…due to…then) are maintained in the risk database.

Table 14: High Level Summary of S5 Risks

Likelihood of Risk Occurrence					
5					
4					
3		13	2, 7, 8	5, 6	
2		17	3, 4	10, 12	
1			9, 11		
	1	2	3	4	5

Consequence of Risk Occurrence

Table 15: RiskTable for S5.

Risk ID	Risk Title	Risk Category	Likelihood (1-5)	Consequence (1-5)	Rating	Possible Mitigation
2	Multiple scatter of sunlight from petal.	Technical	3	3	Med	Undertake study of multiple scattering of sunlight by starshade towards telescope.
3	Solar scatter KPP revision.	Technical	2	3	Low	
4	Solar scatter increases after I&T	Technical	2	3	Low	Effort underway to characterize sensitivity. Need to understand launch fairing env. May need to request extra cleanliness. Before launch edges can be protected with peel away coating under development as an SBIR.
5	Princeton testbed limits contrast performance	Schedule	3	4	Med	Implement facility upgrades to address most likely influences on performance. Continue investigation of alternate facilities.
6	MDL mask fab limits testbed performance	Schedule	3	4	Med	Find and use alternate vendors.
7	SBIR phase 2E funding not available	Cost/Schedule	3	3	Med	Request overguide, reprogram to replace missing SBIR funding, or delay milestone.
8	Unavailability of key personnel/facilities	Schedule	3	3	Med	Find alternative personnel and facilities
9	Stray light through micrometeorite holes	Technical	1	3	Low	Early assy level testing at Northrop to validate models and model multiple reflections. If baseline design insufficient, modify design (e.g. add layers).
10	Slip of pre-Decadal milestones	Schedule	2	4	Med	Verify decadal survey timing. Manage expectations of what constitutes healthy progress on starshade technology development.
11	SLATE unavailable	Cost/Schedule	1	3	Low	Hold on to lab space until after TAC milestone review.
12	MDL etcher unavailable	Cost/Schedule	2	4	Med	Make sure that S5 has adequate priority in MDL queue. Push to ensure regular maintenance of etcher. Pursue alternate vendors.
13	SBIR contractor cannot deliver spokes	Cost	3	2	Med	Use current low-fidelity spokes in medium-fidelity article. Buy higher cost articles outside of SBIR contract.
17	PLUS deployment modeling too complex	Schedule	2	2	Med	

The highest ranked risks (#5, #6) both concern the ability to demonstrate the required suppression/contrast performance at TRL5 (technology S-2). Risk #5 is that the Princeton testbed is unable to demonstrate required suppression/contrast because scattered light (due to issues such as air turbulence or dust) within the testbed sets too high a floor on measurements, even when the mask tested is ideal. Risk #6 is that the Princeton testbed is unable to demonstrate required suppression/contrast even if its measurement noise floor is adequate, due to uncontrollable imperfections in the masks themselves. Using these two risks as examples, a description of the mitigation plans that were defined and subsequently included in the baseline plan are provided. For

Risk #5, the baseline plan is to continue to improve the hardware and operation of the Princeton testbed until it is verifiably capable of measuring the required contrast/suppression, through such means as cleanliness control and automation of mask handling so as not to cause air currents in the optical path. These facility improvement steps were included in the scope of the subcontract and are presently being incorporated into the facility. The expected completion date of the upgrades is tracked in the schedule and the performance will be reassessed at that time and the risk reclassified. For Risk #6, the baseline plan is to continue fabrication and inspection of starshade masks at JPL's Microdevices Laboratory (MDL), and work is ongoing there to optimize mask engineering to sufficient fidelity to meet requirements. The S5 task is also pursuing alternate vendors to fabricate masks as a backup and as of this writing is on contract with an alternate fabrication vendor to evaluate their ability to fabricate mask at the precision required. This risk will be re-evaluated when the most recent fabricated masks are through their measurement cycle.

3.5 REVIEWS, REPORTING, AND DOCUMENTATION

The Manager and technical leads of the S5 Activity will hold weekly meetings to assess status of the technology development work and to deal with short-term issues and priorities. The S5 Activity will also hold Monthly Management Reviews in which each lead will report progress, status and issues against the baseline schedule and cost plan to the S5 manager and institutional line managers. A series of Quarterly reports to the ExEP program, the JPL 7X directorate and the NASA APD Program Executive will be supported by the S5 manager. Other reporting opportunities include: weekly significant events through the ExEP Program, monthly Project Status Reports provided to the HQ PE/PS, hand-in material for periodic non-flight internal reviews (NFIRs) at NASA HQ.

Documentation will be made available to the community to the maximum extent possible, subject to the limitations of the export review process. Final technology milestone reports, for example, will be submitted to the export review and clearance process with the intent to make them accessible publicly.

3.6 EXPORT CONTROL

S5 will review the export classification of its technologies throughout the technology development on an ad hoc basis. These ad hoc reviews will be triggered by the events within the development activities, such as publication or presentation of technical results and shipment of test articles to outside vendors for measurement and analysis. These reviews will be directed through the JPL IECO Officer assigned to the ExEP Office (currently Alex Abramovici).

4 SUPPORTING INFORMATION

4.1 ACRONYM LIST

Acronyms	
ApD	Astrophysics Division
CGI	Coronagraph Instrument
CMM	Coordinate-measuring Machine
CONOPS	Concept of Operations
COR	Cosmic Origins Program
CTE	Coefficient of Thermal Expansion
DRI	Deep Reactive Ion
DRM	Design Reference Mission
DSN	Deep Space Network
EAR	Export Administration Regulations
ESA	European Space Agency
ExEP	Exoplanet Exploration Program
Exo-S	Exo-Starshade
FOV	Field of View
FY	Fiscal Year
GNC	Guidance and Control
HabEx	Habitable Exoplanets Observatory
IECO	Import/Export Control Office
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KDP	Key Decision Point
KPP	Key Performance Parameter
LED	Light Emitting Diode
LOWFS	Low Order Wave Front Sensor
LUVOIR	Large UV/Optical/IR Surveyor
MDL	Microdevices Laboratory
mDOT	Miniaturized Distributed Occulter/Telescope
NASA	National Aeronautics and Space Administration
NGAS	Northrop Grumman Aerospace Systems
NIAC	NASA Innovative Advanced Concepts
NINP	New Ideas and New Partnerships
PCOS	Physics of the Cosmos Program
PLUS	Petal Launch restraint and Unfurl Subsytem
RFI	Request For Information
RFP	Request For Proposal
S5	Starshade to TRL5
SAC	Starshade Acquisition Camera
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer
SEM	Scanning Electron Microscope
SLATE	Starshade Lateral Alignment Testbed Experiment
SMAP	Soil Moisture Active Passive Mission
SNR	Signal to Noise Ratio
SOI	Silicon on Insulator

Acronyms	
SRM	Science Reference Mission
SSWG	Starshade Working Group
STDT	Science and Technology Definition Team
STOP	Structural Thermal Optical Performance
STWG	Science and Technology Working Group
SWOT	Surface Water Ocean Tomography Mission
TBD	To Be Determined
TDEM	Technology Development for Exoplanet Missions
TDP	Technology Development Plan
TET	Trade Evaluation Team
THEIA	Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy
TRL	Technology Readiness Level
WBS	Work Breakdown Structure
WFIRST	Wide Field Infrared Survey Telescope
XRCF	X-ray Crystallography Facility

4.2 RISK RATING DEFINITIONS

4.2.1 *CONSEQUENCES*

Consequence	
Scale	**Technical Performance**
1	Minor impact to design margins.
2	Minor impact to baseline mission performance. Loss of design margin. Requires a minor modification to existing technology.
3	Meets minimum success criteria with margin, but does not meet baseline performance. Does not meet mass, power, volume, or other key performance requirements. Requires a small but new technology development.
4	Meets minimum mission success criteria without significant margin. A mission objective is not achievable. A moderate new technology development is required.
5	Minimum mission success criteria are not achievable. Most mission objectives are not achievable. A major new technology development is required.

Scale	Cost
1	<$50k over allocated Program/Project funding. Can be handled within available reserves.
2	Between $50k and $150k over allocated Program/Project funding. Can be handled within available reserves.
3	Between $150k and $500k over allocated Program/Project funding. Can be handled within available reserves.
4	Between $500k and $2000k over allocated Program/Project funding or threatens to reduce reserves below JPL Design Principles recommended levels.
5	>$2000k over allocated Program/Project funding or exceeds available reserves.

Scale	Schedule
1	Minimal slip on non-critical path. No impact on schedule reserves.
2	<2 month slip on non-critical path. No impact on schedule reserves.
3	Between 2 and 3 month slip on non-critical path, or any slip on critical path that can be handled with schedule reserves without violating JPL Design Principles recommended levels.
4	>3 month slip on non-critical path. Any slip on critical path that threatens to reduce schedule reserves below JPL Design Principles recommended levels. Any slip that impacts delivery dates to recipients within the program.
5	Any slip on the critical path that exceeds reserves. Any slip that affects the launch date. Any slip to Program protected delivery dates.

Scale	Safety
1	Negligible injury.
2	May require only minor first aid treatment.
3	May cause minor injury or minor property damage.
4	May cause severe injury or major property damage.
5	May cause death or permanently disabling injury or destruction of facility.

4.2.2 *LIKELIHOODS*

Scale	Likelihood	Prob. of Occurrence (%)
1	Extremely remote	<1
2	Remote	1 to 10
3	Unlikely	10 to 30
4	Likely	30 to 60
5	High Likely	60 to 100