Starshade Closeout Briefing Report: Technology Status and Applicability to the Habitable Worlds Observatory

June 2, 2025

Summary

The JPL “S5” starshade team, following the completion of their development activity, presented on April 14, 2025, the status of their five technologies and an assessment of remaining work for a possible Habitable Worlds Observatory (HWO) application.

Since its conception in 2016, **all 15 technical milestones had been met achieving TRL 5 for each of the five technologies with respect to the original reference mission – a 26m starshade**. The team evaluated the maturity of the technologies with respect to a 35-m UV/V starshade and a 60-m V/NIR starshade for HWO, identifying the remaining technology development efforts.

The invited subject matter experts consisted of members of the Exoplanet Technology Assessment Committee (ExoTAC; the review board responsible for having reviewed all the S5 milestone reports as well as the development plan) and independent engineers from NASA centers and industry, including experts experienced in supporting the JWST deployments.

The audience agreed that the TRL 5 milestones were clearly met at visible wavelengths for 26m-class starshades. The milestone reports were regarded as high quality, demonstrating a strong level of rigor and well-documented testing. The audience specifically suggested the status of this technology along with future benefits be communicated to the mid-decadal review.

For an **HWO UV/V mission concept application**, the experts concluded:

- **a)** a starlight suppression demonstration conducted at UV wavelengths to verify performance would further exercise the models and reduce performance risk
- **b)** formation flying sensing capabilities demonstrated in S5 should already be sufficient given the larger primary mirror aperture
- **c)** the risk of mechanical scaling from 26m to 35m for a UV application is considered low (however, the scaling law should be revisited)

These remaining technology development risks to mature the five starshade technologies to TRL 5 for an HWO UV/V application are expected to be low.

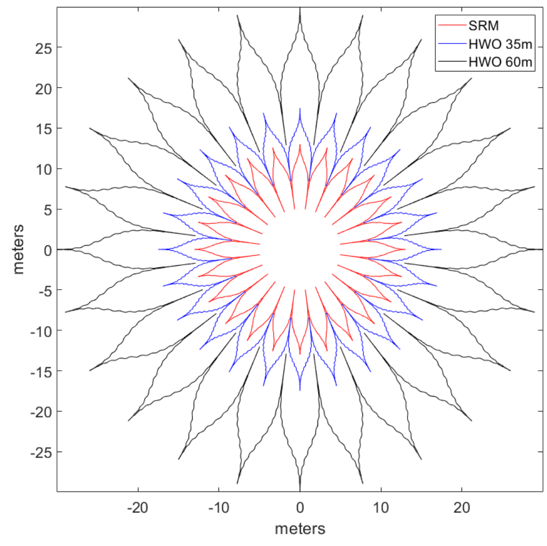

Figure 1: The three starshade sizes considered (SRM: Starshade Reference Mission; 26 m)

For an **HWO V/NIR mission concept application,** the experts agreed with the S5 team that:

a) additional tests demonstrating starlight suppression beyond those conducted at visible wavelengths and those that would be used for a future UV demonstration may not be necessary. NIR demonstrations are unnecessary if both UV and V demonstrations are completed; the validation of models across the range of wavelengths spanning UV and V would retire any concerns regarding extrapolation from V to NIR.
b) formation flying sensing may be easier given the larger primary mirror aperture.
c) the majority of the risk-reducing activities should focus extensively on the large mechanical and deployment demonstrations beyond the S5 activity and approaching TRL 6 demonstrations.

The effort and risk levels of the remaining technology development efforts for a larger HWO V/NIR applications were not assessed but specific suggestions were captured.

Report Context

The Exoplanet Exploration Program (ExEP) Chief Technologist convened a close-out briefing of the Starshade Technology Development Activity. The objectives of the briefing were for:

1) the JPL Starshade “S5” team to summarize the final state of technology maturation with respect to their 2018 Technology Development Plan
2) the S5 team to self-assess the technology maturation for an HWO application

3) the subject matter expert audience to provide feedback on the summary

This report provides a summary record of the briefing and the assessments of the subject matter experts.

Starshade Technology Development Activity (S5) Summary

Prior to S5 standing up, competitively selected SAT awards (solicited via NASA ROSES) were the main means of funding starshade technology development. Key awarded institutions included Northrop Grumman, Princeton University, and JPL. The NASA SBIR program also funded multiple small aerospace partners from industry, notably Roccor, Tendeg, and Zecoat, among others. In all, NASA has spent $19M on starshade technologies through these two programs.

In an effort to accelerate starshade readiness, the Starshade Technology Development Activity was chartered in 2016 with the explicit charge to advance starshade technologies to close the three starshade technology gaps – (1) Starlight Suppression, (2) Formation Flying Sensing, and (3) Deployment Accuracy and Shape Stability, as listed in the Astrophysics Division Technology Gap List.

Nicknamed “S5”, the Activity adopted as reference mission concepts, in the context of requirements and environments, the Roman Space Telescope Rendezvous mission concept (a 2.4-m-aperture telescope, 26-m starshade), and later the HabEx mission concept (4-m telescope, 52-m starshade). Five key starshade technologies were identified to enable a future starshade mission: 1) optical performance and modeling, 2) optical petal edges, 3) formation-flying, 4) petal positioning accuracy and opaque structure, and 5) petal shape and stability (which includes deployment).

The S5 engineers developed a systems-level error budget (Fig. 2) to identify key performance parameters (the elements of the error budget that drive technology) to be demonstrated within the technology program. A Technology Development Plan (Willems, 2018) was written structured around a series of 15 milestones (Fig. 3) that, if achieved, would collectively demonstrate the key performance parameters and mature the five technologies to meet the TRL 5 criteria, and hence, close the three technology gaps for a Roman Rendezvous mission concept. The Plan was reviewed and accepted by the ExoTAC.

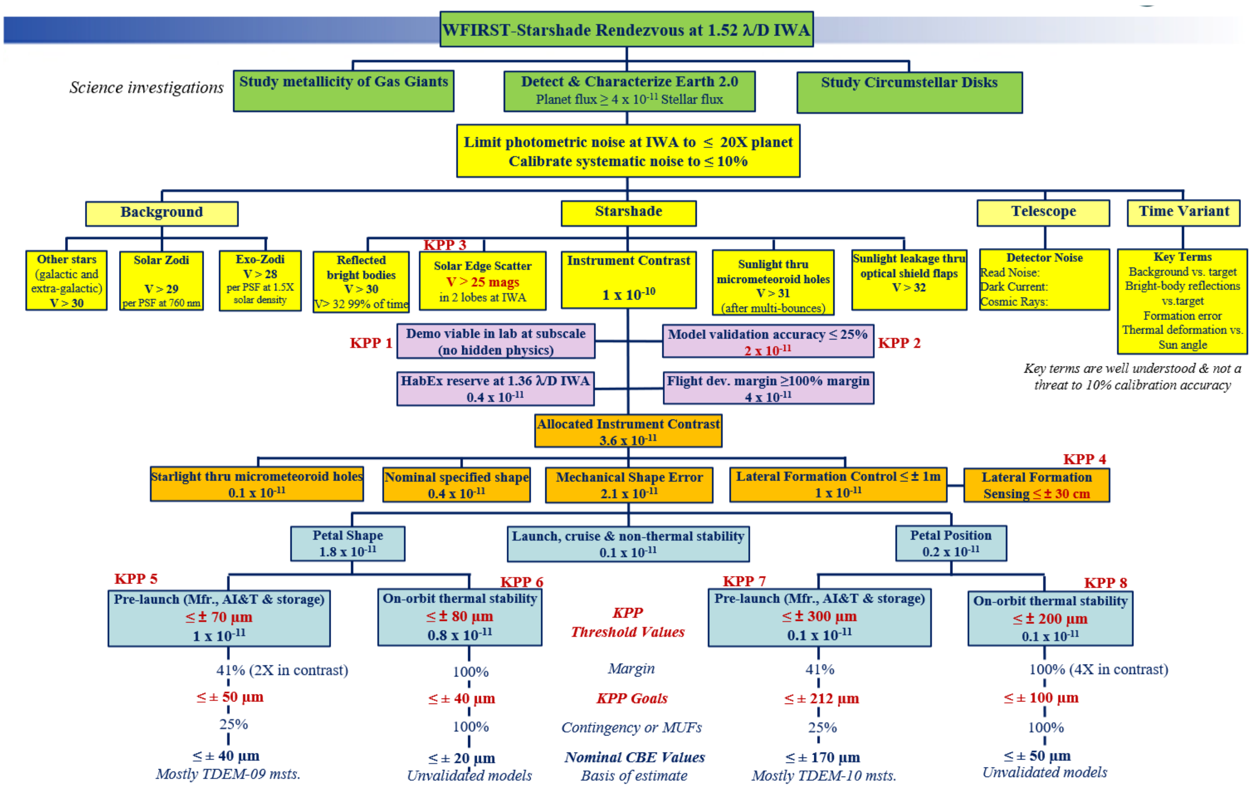

Figure 2: Error budget for a 26-m starshade evaluated for a Roman (ex-WFIRST) Space Telescope mission. The systems view of the error budget helped derive the key performance parameters (KPPs) of the technology development program. This error budget is from the Technology Development Plan developed prior to the work commencing (Willems 2018) and at this date, optical experiments for milestone 2 completion, Model Uncertainty Factors have been updated accordingly. TDEM: Technology Demonstrations for Exoplanet Missions

Technology	MS #	Milestone Description	Closure Report
Starlight Suppression Technology	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.	(Harness, et al., 2019a)
	1B	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning ≥ 10% bandpass at Fresnel number ≤ 15 at the longest wavelength.	(Harness, et al., 2019b)
	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}.	(Harness, et al., 2022)
Scattered Sunlight Technology	3	Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.	(Hilgemann, et al., 2019)
Formation Flying Sensing Technology	4	Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral offset position accuracy to a flight equivalent of ± 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.	(Flinois, et al., 2018)
Petal Position and Shape: Accuracy and Stability Technologies	5A	Petal subsystem with shape critical features demonstrates shape stability after deploy cycles and thermal cycles (deployed) consistent with a total pre-launch shape accuracy within ± 70 µm.	(Mechentel, et al., 2020)
	5B	Petal subsystem with all features demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, & storage) to within ± 70 µm.	(Berg, et al., 2024)
	6A	Petal subsystem with shape critical features demonstrates on-orbit thermal stability within ± 80 µm by analysis using a validated model of critical dimension vs. temperature.	(Webb, et al., 2021)
	6B	Petal subsystem with all features demonstrates on-orbit thermal stability within ± 80 µm using a validated model of critical dimension vs. temperature.	(Carpenter, et al., 2024)
	7A	Truss Bay longeron and node subassemblies demonstrate dimensional stability with thermal cycles (deployed) consistent with a total pre-launch petal position accuracy within ± 300 µm.	(Arya, et al., 2020a)
	7B	Truss Bay assembly demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ± 300 µm.	(Fifield, et al., 2024)
	7C	Inner Disk Subsystem with optical shield assembly that includes deployment critical features demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 µm	(Arya, et al., 2020b)
	7D	Inner Disk Subsystem with optical shield assembly that includes all features demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 µm.	(Ferraro, et al., 2024)
	8A	Truss Bay longeron and node subassemblies demonstrate on-orbit thermal stability within ± 200 µm by analysis using a validated model of critical dimension vs. temperature.	(Webb, et al., 2020)
	8B	Truss Bay assembly demonstrates on-orbit thermal stability within ± 200 µm by analysis using a validated model of critical dimension vs. temperature.	(Fifield, et al., 2025)

Figure 3: The S5 Key Technology Milestones (Willems, 2018) with references to closure reports.

All fifteen milestones were achieved and documented in milestone closure reports and successfully reviewed by the ExoTAC (Figs. 3 and 4). NASA invested $44M in directed starshade technology through the S5 program and work concluded in 2025. Including the SAT and SBIR programs, NASA invested a total of $63M towards starshade technology maturation.

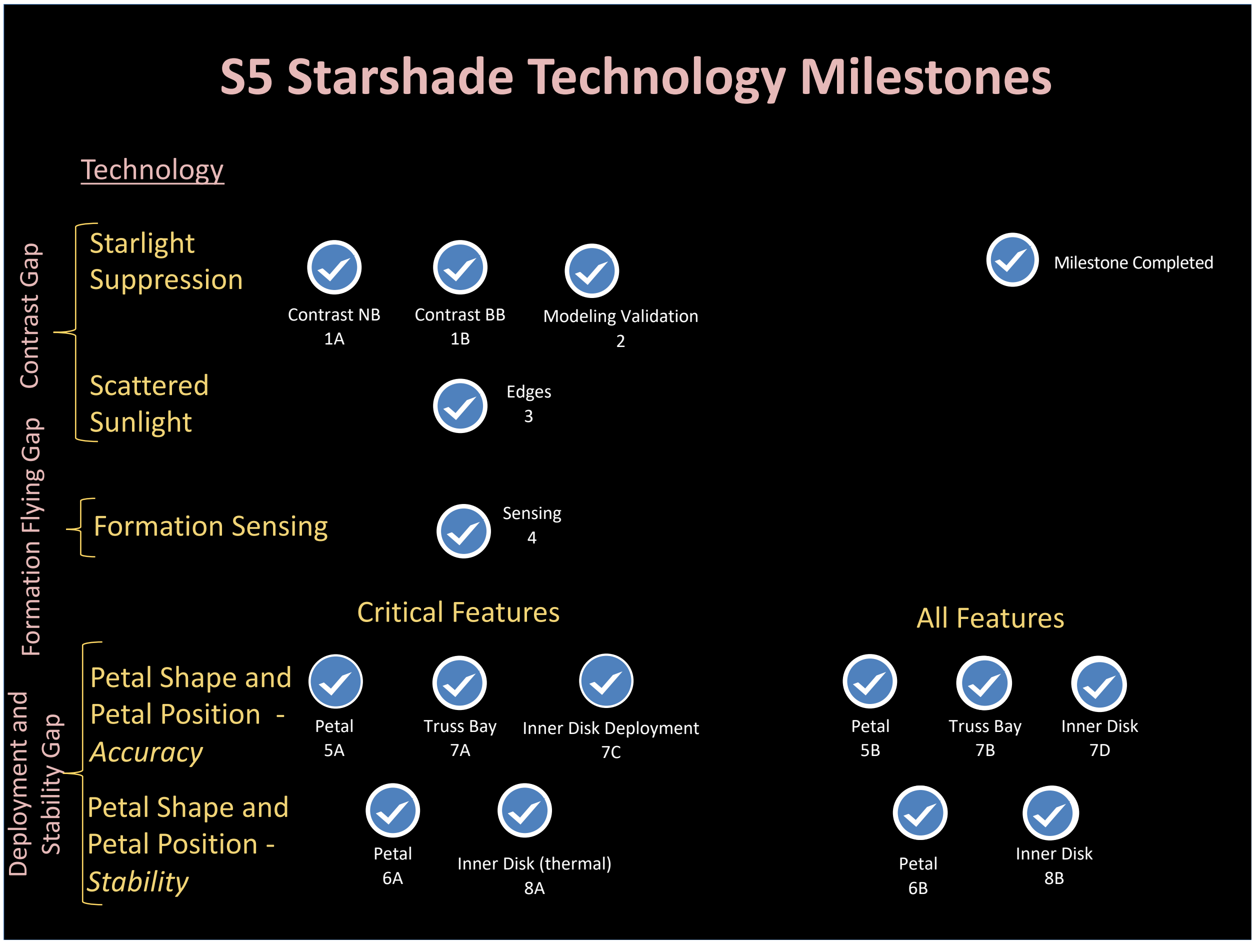

Figure 4: A list of the completed 15 milestones that collectively advanced the five technologies to TRL 5 and closed the three technology gaps for a 26-m starshade.

Mechanical Deployment and Stability Technology Status

Two technologies (petal positioning accuracy and opaque structure, petal shape and stability) were matured by S5 to close the mechanical deployment and stability technology gap. Ten of the fifteen technology milestones were related to these technologies. Their closure reports can all be found here.

Optics and Formation Flying Technology Status

The optical performance technologies are 1) optical performance and modeling, 2) optical petal edges, and 3) formation-flying technology. All five milestones related to these technologies were completed and successfully reviewed by the ExoTAC.

In addition to revisiting the results of milestone demonstrations, at the closeout briefing the starshade team presented three new topics:

1) A contamination analysis of starshade petal edges which allowed the derivation of requirements on contamination and investigated stray light performance degradation due to contamination.
2) An analysis of degradation of optical performance due to micrometeoroids was presented; the starshade maintains both starlight suppression and edge scatter performance after 10 years. The model will be useful for exploring new shield designs.
3) A concept for a next generation optical testbed could be hosted by MSFC's X-Ray and Cryogenics Facility (XRCF). At 260 m long, it is expected to reduce the limiting polarization effects to below 6×10^{-11} at the inner working angle and could include an artificial planet, a spinning starshade, and a demonstration of out-of-band formation sensing and control.

Final Technology Readiness Level

TRL 5 requires that "component and/or brass-board [is] validated in relevant environment," and further requires "Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements." The NASA Technology Readiness Assessment Best Practices Guide (NASA Office of the Chief Technologist, 2020) provides guidance on the performance/function that must be demonstrated, the fidelity of build and level of integration of the test article, the fidelity of analysis and the environment verification (Fig. 5).

The starshade team summarized the achievement of each of the 15 milestones and justified that each of the five technologies meets TRL 5 criteria with respect to the Roman Rendezvous and HabEx mission concept requirements and environments.

Each of the five technologies was shown to meet these criteria at the milestone completion reviews with the ExoTAC.

Starshade Technology	TRL 5 Completion Criteria	Mission Req.	Performance / Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment Verification
	Documented test performance Demonstrating agreement with analytical predictions. Documented definition of scaling requirements.	Generic or specific class of missions	Basic functionality/ performance maintained	Medium fidelity: to predict key performance parameters and life limiting factors as a function of relevant environments	Medium fidelity: brassboard with realistic support elements	Component/ Assembly	Tested in relevant environments Characterize physics of life limiting mechanisms and failure modes.
Starlight Suppression	✓	✓	✓	✓ [High fidelity: subscale effects modeled and understood]	✓ [Medium fidelity mask shape and testbed scaled to preserve Fresnel number]	N/A	N/A
Scattered Sunlight	✓	✓ [26 m starshade missions]	✓	✓ [Life limiting factors expected to be stowed stress and thermal cycles]	✓ [High fidelity edge]	✓ [Component]	✓
Formation Flying Sensing	✓ [Testbed scaled to reproduce Arago spot size w.r.t. pupil]	✓ [starshade missions at Earth-Sun L2]	✓	✓ [KPP validated with Roman formation flying model]	✓ [Algorithm compatible with flight CDS and LOWFS array size]	✓	N/A
Petal Shape	✓ [Good agreement between analyss and test]	✓ [26 m starshade missions]	✓	✓ [Life limiting factors expected to be stowed stress and thermal cycles]	✓ [Medium fidelity test articles at half scale for Roman]	✓ [Assembly]	✓ [Functions and survives over operating full temperature range]
Petal Position (Deployment)	✓	✓ [26 m starshade missions]	✓	✓ [Life limiting factors expected to be stowed stress and thermal cycles]	✓ [Medium fidelity test articles at half scale for Roman]	✓ [Subassembly / Assembly]	✓ [Functions and survives over operating full temperature range]

Figure 5: TRL 5 Definition and Decomposition by Factor (adapted from Table 2.3.2-1 of the Technology Readiness Assessment Best Practices Guide (NASA Office of the Chief Technologist, 2020)) for each of the five starshade technologies. The TRL 5 definition is "Component and/or brass-board validated in a relevant environment.

Summary of Remaining Development Work Towards a HWO Application

The starshade team presented what additional work they believe is needed or would be desirable to achieve TRL 5 for the five technologies with respect to a HWO application, both for a 35-m UV/V starshade and a 60-m V/NIR starshade (Fig. 6). This section also includes valuable comments and feedback from the SMEs, captured in italics. The risk and effort levels were evaluated to be low, medium, or high.

Technology	26-m Baseline (TRL 5)	35-m UV/V (TRL 5)	60-m V/NIR (TRL 5)
	Achieved	Needed/Desirable	Needed/Desirable
Starlight Suppression	• Better than 1e-10 contrast in air at flight Fresnel number. • 4 wavelengths 640, 660,700 725 nm (12.5% bandpass) • Perturbation sensitivity study at 1e-9 – 1e-8 contrast. • Models validated to factor of 1.25 (petal shape) and 2 (petal position) • Limited by polarization due to small mask size	• Optical/NUV Testbed demo (at XRCF for example) over 260 m of beam line (inner mask diam 36 mm) • Goals: 1e-10 contrast at 250 nm, < 3e-10 peak polarization effect in the visible, and true broadband 500-740 nm (inner mask diam 47 mm). • Secondary goals: add 1e-10 exoplanet, spin starshade, in-the-loop out of band formation flying. • Risk: L • Effort: M ($2M, 2 yrs) • Comment: the risk is in the execution, e.g. fabricating the mask, setting up at XRCF. The physics is very low risk.	• No new tests if NUV tests are carried out. • Performance risk for NIR is considered very low. • Comment: The combination of UV tests and already-completed visible tests span a factor of 3 in wavelength. Not expected to learn anything new in the NIR.
Scattered Sunlight	• Measured scatter of coated edges to be equivalent to mag 30 integrated over starshade • Measured in 4 bands • In good agreement with FDTD models. • Tested 80-cm long thermally and environmentally distorted segments.	• Repeat scatter measurements for UV on UV-optimized coatings. • Quality control process for etched edges. • Goals: scatter equivalent to mag 31. • Segment length remains ~ 1 m. • Risk: L • Effort: L • Comment: Effort involves coating design and fab, procurement and fab of edges, modification and calibration of scatterometer.	• No new tests if NUV tests are carried out. • Quality control process for etched edges • Performance risk for NIR considered very low. Segment length remains ~ 1 m. • Risk: L • Effort: L • Comment: 60 m has a lower scatter factor than the 35 m, and coatings are generally considered to be easier.
Formation Flying Sensing	• Through a small-scale laboratory demonstration, measured ability to determine lateral alignment to 30 cm using an out-of-band pupil plane sensing approach. • Separate from S5 tests, the Princeton testbed demonstrated hardware-in-the-loop formation control with 10^{-10} in-band contrast. (Palacios et al 2020).	• Design and requirements are the same. Different band is used but no performance degradation expected. • No new tests.	• Design and requirements are the same. Different band is used but no performance degradation expected. • No new tests.
Petal Shape	• Petal pre-launch shape accuracy and stability • Petal thermal stability on-orbit • This was with a 4-m petal, and section of a 6-m petal • We do not have model validation of Optical Shield influence on petal shape.	• At TRL 5 for a 9-m petal. • No additional tests for TRL 5.	• Design, build, and test an 8-m petal. • Demonstrate manufacture accuracy and thermal and shape stability, test hinge interfaces • Medium fidelity, all defining features • Validate models of optical shield influence on shape. • Risk: L • Effort: H • This is a repeat of all the S5 petal milestones with a larger petal.

Petal Position (Deployment)	• Pre-launch inner disk accuracy and on-orbit stability • Inner disk thermal stability on orbit. • This was with a 10-m disk including a multi-layer optical shield but no closeout shield. • We do not have model validation of Optical Shield influence on disk shape.	• At TRL 5 for a 17-m disk.	• Test a medium fidelity 14-m truss with four 8-m petals. • Medium fidelity truss bay pair (for 14-m truss) with all defining features. • Demonstrate manufacture accuracy and thermal and shape stability. • Validate models of optical shield influence on shape. • Demonstrate solar panel integration including cabling. • Risk: L • Effort: H • This is a repeat of all the S5 petal milestones with a larger petal.

Figure 6: Remaining development work towards HWO as presented by the S5 team

Starlight Suppression

- Desirable tests would include a UV (250 nm) demonstration of starlight suppression with a larger facility (possibly MSFC's XRCF) enabling a slightly larger subscale starshade than previously demonstrated. This would both validate UV performance and gain more confidence in the polarization effects that limited earlier tests. A true broadband demonstration across the visible band could be performed with the same setup. This is considered a low-risk activity, but medium effort. Performance in the NIR is considered low risk and unnecessary if UV and broadband V demonstrations are conducted.
    - **SME suggestion:** *Further model validation of optical performance should be undertaken. The optical functionality relies on scaling subscale contrast performance demonstrations. The physics is well-known and was demonstrated in earlier tests. But model uncertainty factors that enter into the S5 error budgets could be reduced with more model validation, particularly in a larger scale testbed where polarization effects would be expected to drop off quickly. This could be achieved during the UV-V demonstration.*

- For petal edge scatter, the scatter measurements would need to be repeated in the UV. A quality control process for etching the petal edges should be developed. This is considered low risk and low effort.
    - **SME suggestion:** *Stray light should be studied further. The key paths for scattering sunlight from the starshade petal edges into the telescope were identified in advancing the optical petal edge technology, but multiple-*

bounce paths at high resolution need to be simulated due to the brightness of the Sun. This may require any surface that can see sunlight during science observations to be evaluated. This is often limited by computational resources. This would be a TRL 6 level assessment.

Formation Flying Sensing

- No new tests are needed for formation sensing. The architecture can remain the same for both HWO starshades UV/V and V/NIR, as the design and requirements remain the same as those previously demonstrated. A larger primary mirror increases the photon flux, compensating for the larger observatory-spacecraft range.

Deployment Accuracy and Shape Stability

- Petal shape accuracy and stability does not require additional tests for a UV/V starshade – the petal size is nearly the same as the original S5 design. However, for the larger V/NIR starshade, a half-scale petal (8 m) with all defining features should be built and manufacturing, deployment cycles, thermal cycles, stowage should be demonstrated. Models of the optical shield influence on deployment can be validated.
    - **SME suggestion:** *A comprehensive review of scaling laws should be undertaken. The scaling assumptions used in linking milestone demonstrations to the full-scale design should be carefully evaluated for applicability to the much larger V-IR starshade to determine sub-scale TRL 5 applicability for an HWO application. In some cases, even a 2x mechanical scaling may require additional analysis.*

- Similarly, inner disk accuracy and stability does not require further demonstrations for a UV/V starshade as it is very similarly sized to those used in the S5 tests. But for the V/NIR starshade, the tests should be repeated with four half-scale (8 m) attached to a half-scale (14 m) inner disk truss. Deployment, as well as manufacturing accuracy and thermal and shape stability will be demonstrated. This enables the team to validate models of optical shield influence on shape, and to demonstrate solar panel integration including cabling.
    - **SME suggestion:** *Future mechanical deployment and stability demonstrations should use a higher fidelity optical disk. This should include a disk thickness that meets requirements set by micrometeorite rate studies, and any solar cells should be in place. The load path from the optical disk to structures that set the critical dimensions of the starshade need to be well understood and the flexible inner disk structure creates*

challenges. This is most important for scaling the design to larger starshades and for higher levels of integration required for TRL 6.

- Both mechanical tests are low risk activities which involve identical tasks for the smaller petal and inner disk as already carried in the previously completed milestones. The new mechanical tests are a high effort level as they require investment in new facilities that can accommodate and measure the larger test articles.

In addition, two systems-level activities were suggested:

1) launch load analysis for larger starshades
2) solar photovoltaic cells should be integrated with the inner disk optical shield to confirm that deployment is unaffected

Additional Detailed Comments from SMEs

- TRL 5 is clearly met for S5’s 26-m starshade; a TRL 6 effort may uncover additional challenges.
- This information should be presented to the mid-decadal review.
- The formation sensing demonstrations look very good.
- The team has done an excellent job projecting the application of the S5 effort to HWO as either a UV/V or V/NIR starshade.

Related to scaling

- Sometimes scaling by only 25% when soft goods are involved leads to new questions, though starshade inner disk not under tension like JWST.
- Even scaling the truss bays may lead to unexpected changes.
- A 2x scaling of a deployable with flexible materials feels OK for TRL 5, but feels uncomfortable for TRL 6.
- 8 years ago the program and the ExoTAC articulated good arguments for why ½ scale demonstrations were sufficient for TRL 5, but that context wasn’t captured in the closeout. It would be valuable to revisit those arguments and assumptions now that the program is completed and update whether they still apply.

Optical Shield:

- A low/medium fidelity optical shield was used for the truss deployments, and no optical shield was used for the petals, appropriate for this level of demonstration.

Though the shield isn't truly a membrane deployment, it's not a deterministic deployment either. A key lesson learned from JWST was the frill, which when going cold exerted a load onto the PM backplane and segments. It is important to understand that interface between the shield and starshade structure, and future efforts should include a higher-fidelity optical shield (consistent with the micrometeoroid assessment) as part of demonstrations and/or analysis.

Edge coating/scatter

- An edge coating that functions in a broad band all the way from UV through the NIR may be challenging.
- Scattered light analysis should be extended: something as bright as the Sun requires many rays and sampling enough of them

Optical model validation

- Ideally, optical modeling would be redone in a larger testbed to further test the conclusions about the limiting factors to model validation in the Princeton testbed. The tests could be repeated in NIR and UV, as appropriate for the application.

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Note: this bibliography includes links to the starshade closure reports. Other details and analyses can be found in a series of papaers in special section of Journal of Astronomical Telescopes, Instrumentation and Systems (JATIS) in June 2021.

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