Maturity Assessment of Starshade Optical and Formation Flying Technologies for Habitable Worlds Observatory

August 16, 2023

Summary

The JPL "S5" starshade team presented an assessment of the maturity of three starshade technologies to an independent, mostly external board, made up of a peer group of both NASA and non-NASA engineers. The reviewed technologies were: 1) optical performance and modeling, 2) optical petal edges, and 3) formation-flying technology, with respect to anticipated Habitable Worlds Observatory (HWO) requirements. The Starshade Technology Activity achieved all development milestones for those three technologies with respect to requirements of a hypothetical starshade mission operating with the Nancy Grace Roman Space Telescope (Roman Rendezvous) and for the HabEx mission concept.

This board assessed the maturity of the three technologies with respect to assumed HWO requirements and by similarity with Roman/HabEx requirements. Mechanical deployment and petal shape stability technologies were not assessed at this time.

The board concluded:

1. **For operations in the visible band, the remaining technology gaps for starshade optical and formation sensing technologies for HWO are likely small. Any effort to achieve TRL 5 by a future HWO mission is likely to be modest and risks are low.** The starshade team overall presented convincing arguments for the high degree of similarity between a starshade for HWO and the Roman/HabEx starshade reference design towards which the starshade team has been working. This is especially true for visible-band wavelengths, at which the starshade milestone demonstrations occurred and that has been the focus of modeling and studies.
2. **Formation-sensing technology is very low risk for HWO.** The starshade team presented two independently demonstrated techniques that were tested for sensing the relative lateral position of the telescope and starshade for formation flying. Either approach appeared to offer sufficient accuracy for a potential HWO architecture.
3. **Ultraviolet (UV) and near-infrared (NIR) band operations of a starshade are likely to require further optical performance demonstrations and analysis, given that all the demonstrations were conducted in the visible band.** This is particularly true for petal-edge sunlight-scatter mitigation and how edge coatings and contamination effects scale into the UV. Related to this is studying how overall contamination requirements change with a larger starshade. Similarly, extending operations into NIR wavelengths is likely to require further demonstrations and analysis.
4. **The board declined to assign a specific TRL with respect to HWO for these three technologies at this time.** The starshade team made reasonable assumptions about HWO requirements and mission parameters based on the decadal survey

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recommendations for this mission, however, a formal TRL assessment will be more appropriate as the mission and its requirements become more developed. In addition, some board members questioned whether TRL is applicable to the modeling and algorithms presented here without a specific hardware or software implementation. As the remaining mechanical deployment and shape stability starshade milestones are completed in the future, a TRL evaluation would become relevant. Others felt that the algorithms themselves do in fact constitute a new technology that can be assessed against TRL guidelines.

Additional comments are listed in the "Comments from Board Members" section below.

Background

The Exoplanet Exploration Program (ExEP) Chief Technologist convened an independent board of engineering peers to assess the maturity of three starshade technologies: 1) optical performance and modeling, 2) optical petal edges, and 3) formation-flying technology, with respect to HWO requirements. These three technologies have been developed with the intention of closing two technology gaps in APD's Technology Gap List - Starlight Suppression and Formation Flying. Mechanical deployment and petal shape stability technologies, intended to close the third and last technology gap, Deployment Accuracy and Shape Stability, were not reviewed at this time.

NASA created the Starshade Technology Development Activity in 2016 (nicknamed "S5") to mature all key starshade technologies to TRL 5. The Activity is structured around a series of milestones that, when successfully achieved, will demonstrate that the technology meets TRL 5 criteria. The original Technology Development Plan and the closure documentation for each milestone was reviewed by the Exoplanet Technology Assessment Committee (ExoTAC). Seven years later, they have achieved all four milestones in the areas of formation flying and optical performance, including optical petal edges and modeling.

In 2016, the Activity was working towards the requirements of a Roman Rendezvous mission (a 2.4-m-aperture telescope) and later the requirements of a HabEx concept (4-m telescope). However, the Decadal Survey in Astronomy and Astrophysics recommended that NASA develop technology to enable an exoplanet direct-imaging mission with a primary mirror of roughly 6-m diameter. NASA has adopted the name Habitable Worlds Observatory for this recommended future mission.

The charge to this expert board is to evaluate the Starshade Technology Activity's maturity with respect to anticipated HWO requirements, and whether TRL 5 criteria, met for Roman Rendezvous and HabEx, are still met.

Summary of Starshade Team Presentation

The starshade team presented a reference design for HWO based on preliminary assumptions about the HWO mission. The key differences from the original starshade reference design are:

- Size of the starshade and separation from the space telescope. The HWO starshade can be about 60 m in diameter (slightly larger than the proposed 52-m HabEx design) and operate at a greater separation from the space telescope than the Roman/HabEx starshade (95 Mm vs. 76 Mm for HabEx in the visible band). The separation is adjusted to maintain the inner working angle as the wavelength of observation changes. A HWO design could have the same petal size (24 16-m-long petals) as the design in the HabEx report, but with a larger inner disk (28-m diameter vs. 20-m diameter).

- The extension of observation into the UV and NIR (250-1800 nm). The lower wavelength limit of the UV band recommended by Astro2020 was 200 nm, though the starshade team is currently working towards 250nm. This is likely a matter for the future START team to resolve.

The Starshade Team presented summaries of the completed milestone demonstrations relevant to the three technologies in question (milestones 1-4 from the Starshade Technology Development Plan) and made arguments about their applicability to a HWO mission.

- MS-1: Contrast demonstration. The milestone aims, via a subscale demonstration of a 2.5-cm etched silicon starshade, to demonstrate the starshade shape that will meet contrast performance at a flight Fresnel number. The team demonstrated better than 1e-10 instrument contrast over 75% of the search space at the petal tips, but over 25% of the search space, unexpected bright lobes consistent with vector diffraction appeared. Models indicate that the vector diffraction was due to extremely small features within the subscale starshade and will scale to negligible levels at flight scales. Slightly larger future subscale demonstrations would verify this reduction. Due to diffraction's scale invariance at fixed Fresnel numbers, the starshade team argues that the demonstration applies to a HWO starshade.
- MS-2: Optical model validation. The milestone used the same testbed as milestone 1 with deliberately misshapen subscale starshades to validate the starshade optical model to within 25% for petal shape errors and to within 100% for petal position errors. Similar to milestone 1, this result also applies directly to a HWO design.
- MS-3: Stray sunlight control. This milestone addresses sunlight scattering from the petal edges. A flight starshade is designed to have ~1-m petal edge segments made of amorphous metal with a sharp edge that minimizes that scatter. The milestone demonstration was to build and measure the reflectivity of an edge segment that traces to a sunlight scatter equivalent of ≥ 25 V_{mag}, including secondary reflections from the edge support structure. Later, a better result was achieved using a multilayer coating. The multilayer result corresponds to a ≥ 30 V_{mag} sunlight lobe in the case of the HWO design. The milestone demonstration was performed over the 500-1000 nm bandwidth and did not include UV or NIR measurements.
- MS-4: Lateral formation sensing. The team demonstrated formation sensing accuracy that meets Roman/HabEx requirements with a combination of modeling and subscale lab demos. The sensing technique uses a pupil plane camera which takes advantage of a Poisson spot that becomes relatively bright at wavelengths outside the science band of the starshade. Modeling of a control process based on this sensitivity shows that the requirements for thruster firing frequency and the relatively small gravity gradient in an L2 halo orbit falls within the realm of standard engineering. In addition, a separate SAT-funded focal-plane formation-sensing technique (PI Jeremy Kasdin/Princeton) also meets the requirements. In the case of HWO, the scaling of the starshade size and telescope diameter maintains the ability to achieve centroiding of the Poisson spot such that sensing requirements are still met.

In addition, the starshade team provided responses to the TRL-5 questions from NASA's Technology Readiness Assessment Best Practices Guide in backup charts, arguing they meet the criteria for TRL 5.

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Detailed Comments from Board Members

- A future HWO project office considering starshade technology is likely to have to revisit the maturity of these technologies as the mission becomes better defined.
- Extending the wavelength band to the UV will require further subscale testing at that specific wavelength. While in principle, the milestone 1 and 2 demonstrations should scale with wavelength according to the validated models, testing at the operational wavelengths would further reduce risk and potentially uncover unexpected challenges.
- Extending the wavelength band to the NIR will require further modeling and subscale testing at the operational wavelength to better understand thermal self-emission, solar heating, and NIR stray light. While in principle, the milestones 1 and 2 demonstrations should scale with wavelength according to the validated models, testing at the operational wavelengths would further reduce risk and potentially uncover unexpected challenges.
- The starshade reference architecture includes amorphous solar cells mounted on the inner disk. Future demonstrations should include these.
- While a starshade could be incorporated into a HWO mission as a later servicing mission with the starshade launched later, the initial HWO mission may need to consider instrumentation for UV operations from the very beginning.
- To help with extending the stray-sunlight control milestone into the UV, the milestone could be broken into two sub-milestones: one general stray-light modeling and validation milestone and one coating milestone to verify the performance, process, integrity, and lifetime of edge coating candidates.
- The increased size of the starshade could potentially have an impact on the stray-light control milestone, in that a larger system will be harder to keep clean and/or ensure coating integrity.
- If future funding allows, it is recommended that a larger-scale system be tested which would address some of the drawbacks discussed in the presentation. The presentation stated some of these issues could be addressed with a testbed with a 2x starshade diameter and 2 x testbed length. It was suggested to revisit the applicability of a facility such as the XRCF at MSFC which has a 518.2-m long feed tube which can be evacuated to 10^{-7} torr. This would allow increasing the starshade diameter and testbed length by up to 6x and enable testing in vacuum. The expected number of starshade petals for an HWO application might also be implemented. In all, this would result in additional data points to evaluate performance and modeling and facilitate increasing model accuracy.
- The error budget presented in VG 6 did not clearly break out the impact of stray sunlight on the contrast requirement so the origin of the allowable equivalent magnitude of the straylight allocation for HWO was not specifically shown there. VG 37 did include numbers for the stray sunlight as well as local zodi and exozodi, but was labeled as an “example” noise budget and not stated as an allocation based on derived requirements. However, that appears to be where the V_{mag} = 30 derived requirement originates. Assuming that is an appropriate number for HWO, the presentation showed that previous testing of uncoated etched amorphous metal edges would not meet this requirement – therefore the petal edges need to be treated/coated in some manner. A suitable multi-layer edge coating was designed, deposited, and tested both for scatter and durability as applicable to the 500-1000 nm range. So, for that wavelength range, the sunlight glint control meets the proposed HWO requirement.

- The edge coating was applied to metal-edge samples of up to 0.75-m (0.5-m in one report and 0.75-m per a communication with Dave Sheikh of ZeCoat). The fidelity of those samples qualifies them as brassboards per the TRL-5 requirement. Those samples were tested after coating for durability and subsequently for scatter (at specific wavelengths in the 500-1000 nm range). So, the suitable, applicable environmental and performance testing was done. In addition, a 9-layer coating design has been developed by ZeCoat to extend broadband performance down to about 200 nm. However, this has not been deposited nor tested so the TRL-5 evaluation at this time is only for the 500-1000 nm range. Further coating development and verification will be needed in the future to extend the wavelength range.
- A future HWO mission should be designed to be starshade-compatible.

Board Membership

Matt Bolcar (NASA/GSFC), Simone d'Amico (Stanford), Opher Ganel, (NASA/GSFC), Tupper Hyde (NASA/GSFC), Steve Kendrick (aerospace consultant), David Miller (NASA/JPL), Omid Noroozian (NASA HQ), Joe Pitman (aerospace consultant), Rachel Rivera (NASA/GSFC), Dan Scharf (NASA/JPL)

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