NASA's starshade technology development activity

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Abstract. NASA is developing starshade technology to Technology Readiness Level 5 within a directed activity called S5. The objective of S5 is to mature starshade technology to the level that exoplanet imaging missions, such as Starshade Rendezvous and HabEx, can begin the formulation phase. This paper outlines the S5 activity as a whole, to show how it closes all starshade technology gaps in a mutually consistent way. It serves as a companion paper to several other papers in this special section that report progress in specific starshade technologies. [DOI: 10.1117/1.JATIS.7.2.021203]

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1 Introduction

The search for life elsewhere in the Universe is one of the major goals of NASA, indeed of humankind. A major part of this is the search for habitable worlds orbiting other stars. There is a lively debate over what the general conditions are that can support life, but the example of our own planet leads astronomers to search for rocky planets orbiting their host stars at distances that allow liquid water to exist on their surfaces. Direct imaging and spectroscopy of such exoplanets can reveal the presence or absence of water vapor and biosignature gases. However, these exoplanets are very faint compared to their host stars and also very close to them, and so high-contrast imaging is necessary for these observations.

A starshade is a spacecraft that flies between a telescope and a distant star, blocking the star's light from entering the telescope. The starshade's size and distance are chosen so that the starshade subtends a smaller angle than the orbit of an exoplanet orbiting the star. The starshade thus does not block the exoplanet's light, allowing it to be observed free from the star's glare, much as the moon makes the solar corona observable during a solar eclipse. Typical starshade mission concepts employ starshades tens of meters across, flying tens of millions of meters from the telescope.

As seen from a star 10 parsecs away, the Earth at quarter phase is 10^{-10} times as bright as the Sun, at a separation of 100 mas. This roughly sets the high-contrast imaging requirements for direct imaging of rocky exoplanets in habitable zones. Both these requirements will vary with the star's distance and stellar class and with the exoplanet size.

If the starshade were a round disk, the diffraction of starlight around the starshade would lead to a bright spot of Arago at the center of its shadow, and the exoplanet would still be lost in the resulting glare. This diffraction can be dramatically reduced by giving the starshade a flower-like shape with "petals" around its circumference. The petal of the starshade is shaped to smoothly reduce the azimuthally averaged opacity of the starshade from 100% at the petal's base to 0% at its tip, in a way that apodizes the starshade's diffraction pattern and removes the spot of Arago. A description of starshade apodization has been given by Cash.[1]

This special section of the *Journal of Astronomical Telescopes, Instruments, and Systems* that focuses on starshades includes several articles[2–6] describing work being conducted under NASA's Starshade To Technology Readiness Level (TRL) 5 Technology Development Activity, also known as S5. This article presents an overview of the S5 Activity that provides a common background and context to the work described in those articles.

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2 Technology Gaps to Starshade Missions

NASA uses a TRL scale to describe the maturity of diverse space mission technologies in a consistent manner.[7] TRL ranges from level 1 for the identification of a basic theoretical concept, up to level 9 for technology that is successfully flight proven. Intermediate levels going up the TRL scale reflect demonstration of technology using increasingly flight-like test articles tested in increasingly flight-like environments. NASA's Astrophysics Division prefers that all technologies needed for a mission be at TRL5 or higher before that mission enters formulation. A technology is considered to be at TRL5 if its basic functionality is demonstrated using medium-fidelity prototypes that have been tested in the relevant mission environments that real flight articles employing the technology would experience during a mission. Technologies not yet at TRL5 for a mission are referred to as technology gaps to that mission. NASA's Exoplanet Exploration Program (ExEP) maintains a list of technology gaps for exoplanet missions, which can be found in its Technology Plan Appendix.[8] The ExEP Technology Plan Appendix lists three technology gaps for starshade missions: starlight suppression, formation sensing and control, and deployment accuracy and shape stability. We briefly describe each in turn.

Starlight suppression technologies are those needed so that the starshade can reduce starlight to a sufficiently low level to make exoplanet imaging possible. Two separate technologies are needed to close the starlight suppression technology gap. One technology is the capability to model and measure optical performance sufficiently to define starshade shapes that cast adequately dark shadows in the exoplanet's host star's light. The other technology is the ability to build and deploy starshade edges that glint light from our own Sun at low enough levels to allow exoplanet imaging.

Formation sensing and control technology is needed to keep the starshade aligned along the telescope's line of sight well enough to keep the darkest region of its shadow centered on the telescope's aperture. In practice, this technology gap is closed by the ability to sense the starshade's transverse position along the telescope line of sight to within about a meter.

Deployment accuracy and shape stability technologies are those necessary to fabricate starshades that deploy in space to their operational shapes with sufficient accuracy to realize the required starlight suppression, and then maintain that shape against distorting influences such as thermal deformations. The ExEP Technology Plan Appendix identifies two distinct technologies to close this technology gap: one is the precise fabrication of stable petal shapes, and the other is the accurate and stable deployment of those petals to their operational positions.

NASA typically funds exoplanet technology development to TRL5 through competed Technology Development for Exoplanet Missions (TDEM) grants. Prior to 2016, starshade technology development was funded primarily in this way. In 2016, NASA approved a proposal by the ExEP to restructure NASA's investments in starshades into a more focused activity, with a directed budget, formal milestones, dedicated management, and an enhanced systems engineering function. This led to the formation of the S5 Activity, and to the adoption of the S5 Technology Development Plan in 2018.[9] The ExEP maintains a standing review board, called the Exoplanet Technology Assessment Committee (ExoTAC), to decide when ExEP technology efforts meet their development milestones. The ExoTAC reviews S5 milestones as well, and makes the determination when a starshade technology has reached TRL5.

One advantage of organizing S5 as a directed activity is that it facilitates closing the three starshade technology gaps in a mutually consistent way, so that all of them can readily be employed together in one mission. For example, a solar glint reduction technology that reduces the scattered sunlight to very low levels, but relies upon brittle materials that cannot flex, would be incompatible with S5's baseline mechanical deployment technology, in which the starshade petals are wrapped around the folded inner disk prior to launch and then unwrapped to deploy once in space. Likewise, a petal shape that from an optical perspective provides very good starlight suppression, but has an extremely long, thin tip, could prove unfeasible to realize in a stable and deployable mechanical structure.

The readiness level of a technology is evaluated with respect to the specific mission in which it will be used. S5 takes the working assumption that the Starshade Rendezvous Mission[10] (SRM) will be NASA's first starshade mission. The SRM would fly a 26-m diameter starshade to rendezvous with the Nancy Grace Roman Space Telescope, as an extension to its prime mission. The Roman telescope would use its coronagraph instrument (CGI) for the starshade observations, with its coronagraph masks and stops withdrawn from the focal plane optical path. Practically, this means that S5 derives its technological Key Performance Parameters (KPPs), the fidelity of starshade test articles, and the relevant and stressing environments, largely from the SRM mission concept. The KPPs and environments derived by S5 for SRM also apply for the Habitable Exoplanet Observatory (HabEx) mission.[11] The main difference between the two missions that impacts the technology development is in the size of the starshade, with the HabEx starshade being twice as large as the SRM starshade. Thus, a full-scale test article for SRM will be only half-scale for HabEx and therefore of lower fidelity. Nevertheless, S5 considers its test plan to be sufficient to demonstrate TRL5 for HabEx and SRM, as the scaling issues are well understood in this range.

The adoption of SRM and HabEx as the reference missions for S5's technology development sets many of the test parameters that are reported in the companion articles to this article. The range of solar angles relative to the telescope line of sight is taken to encompass the range assumed by HabEx mission concept final report, which contains the whole range of angles assumed by SRM. The temperature ranges over which the edge segments and petal and truss prototypes were subjected was driven by the expected temperatures in the Sun-Earth L2 halo orbit in which both SRM and HabEx would operate, over the full range of solar angles. The flexure tests of the edges and petals were chosen to match the greatest flexure seen in the stowed SRM starshade, which is greater than that of the HabEx starshade.

The allocation of the starshade key performance parameters is derived from an assumed top-level requirement to be able to detect an exoEarth at the inner working angle of the starshade. In flowing down this top-level requirement to lower-level requirements on the various technologies developed by S5, the impact on exoplanet imaging by factors other than S5 technologies is also considered. These factors include astrophysical foregrounds and backgrounds such as zodiacal and exozodiacal light. There are also factors that impact starshade performance that do not require the development of new technology, but still must be accounted for. Examples of these factors are planetary light reflecting from the starshade toward the telescope and sunlight scattering from micrometeoroid holes accumulated in the starshade's opaque shield over its mission lifetime. Figure 1 shows the KPP flowdown as it was understood at the adoption of the S5 Technology Development Plan. S5 reassesses its KPP flowdown on an ongoing basis. The companion article by Hu et al.[6] shows one such reassessment.

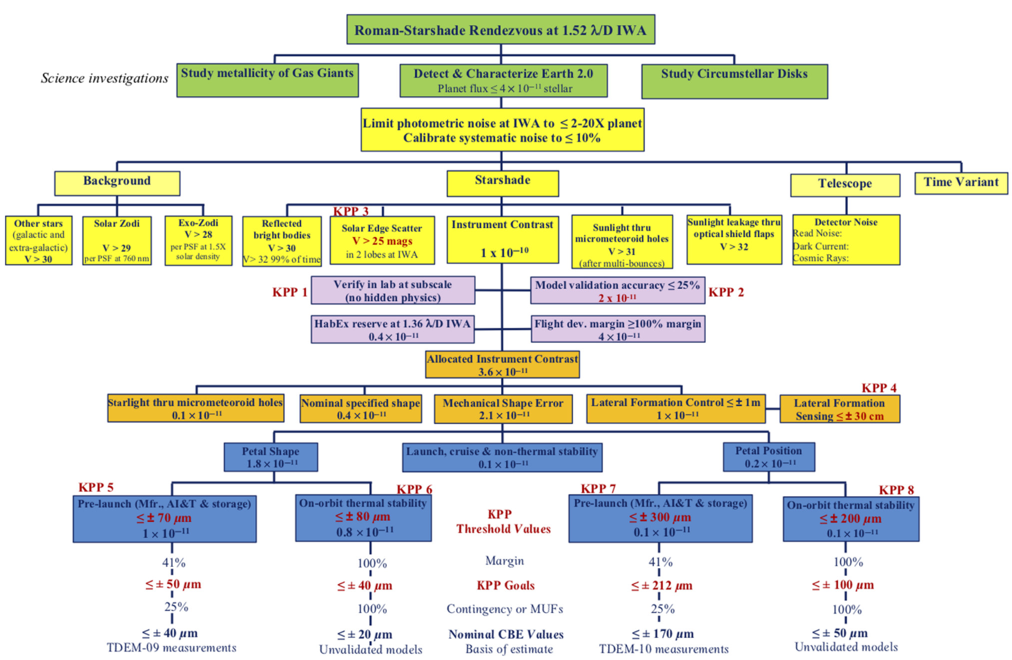

Fig. 1 Flowdown of starshade key performance parameters used by S5. A more detailed explanation of the various terms can be found in the S5 Technology Development Plan.[9]

The KPP flowdown in Fig. 1 includes a "HabEx reserve" of contrast that accounts for HabEx's slightly higher shape error sensitivity relative to SRM. It is now understood that HabEx is less sensitive to solar glint than SRM,[6] and that this offsets the higher shape error sensitivity, such that the contrast reserve is not necessary. S5 is considering reallocating the HabEx reserve to augment the mechanical shape error allocations for KPPs 6 and 8 to significantly increase the performance margins there.

2.1 *Starlight Suppression*

Theoretical modeling has identified a variety of starshade shapes that will realize apodization functions that suppress the starlight to the very low levels needed by direct imaging missions. However, the effort to show experimentally that these shapes really do suppress starlight to the levels that the models predict is still ongoing. The companion article by Harness et al.[4] describes the experiments recently done that showed that starshades with these shapes do achieve 10^{-10} contrast at their inner working angle. Harness et al. also describe some of S5's current activities, which are validating the optical models by showing that the contrast of a starshade changes in a predictable manner as its shape is changed and that optical models verified by tests at a laboratory scale can be applied to starshades operated at flight scale.

The nominal starshade missions that NASA is considering would operate at the Sun-Earth L2 point, where the starshade would be exposed to direct sunlight. The Sun is so much brighter than a typical rocky exoplanet (about 56 magnitudes), that the sunlight glinting off features on the starshade into the telescope must also be suppressed to a very high level. Most of the sunlight suppression is accomplished by relatively simple engineering choices, such as always doing observations with the Sun illuminating the backside of the starshade (see Fig. 1 in Shaklan et al.[2]), and ensuring that no features on the telescope-facing side protrude into the sunlight. What then remains is the glint from the very edges of the starshade, which are directly illuminated by the Sun and at the same time visible to the telescope. The development of robustly deployable edges that limit this scattered sunlight to acceptable levels is the other technology needed to close the starlight suppression technology gap. Two companion articles to this one describe work on this technology. Shaklan et al.[2] describe how S5 has brought the solar glint technology to TRL5 by constructing edge assemblies with very sharp terminal edges etched from amorphous metal foil. These edges have low solar glint by virtue of their very sharp radii of curvature, which minimizes the available surface area that can directly reflect sunlight into the telescope. Notwithstanding this accomplishment in closing the technology gap, the solar glint is still expected to be a relatively bright feature in a starshade image, and so S5 is working to reduce the glint still further. McKeithen et al.[3] describe the development and test of antireflecting coatings applied to these edges that have the potential to reduce the solar glint several times further.

2.2 *Formation Sensing and Control*

The formation flying technology gap was closed shortly after S5 began, with the successful review of S5's first milestone report, which was on starshade lateral position sensing and control. The only technology that needed to be developed to bring the formation flying to TRL5 was the lateral sensing of the starshade during exoplanet observations. Sensing the starshade's tens of megameter distance from the telescope can be straightforwardly achieved with sufficient accuracy using S-band ranging transponders. The disturbances to the position of the starshade relative to the telescope/star axis at the L2 orbit are dominated by gravity gradient forces and solar pressure with a worst-case relative acceleration of 3 μg, and to maintain lateral positioning to within 1 m requires brief thruster application only about once every 600 s, and 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 such as thrusters needed for formation flying is also already flight-qualified.

S5's technology for lateral position sensing measures the starshade's lateral position by detecting features in the starshade's shadow using a sensor in the pupil plane of the telescope. These features are made readily visible by observing the shadow at a wavelength outside the starshade's stopband where they are relatively bright and easy to see. These images of the shadow are compared to a library of simulated images with various starshade offsets, and the library image that best matches the measured image provides the size and direction of offset. Bottom et al.[12] describes this technique and demonstrated that it can provide the required sensitivity in an optical testbed operated at the Jet Propulsion Laboratory (JPL). The results of this experimentally validated optical model were then used by Flinois et al.[13] as input to a computational guidance, navigation, and control model to show that an L2 starshade mission using this method with its demonstrated sensitivity could indeed robustly control the starshade's position within requirements.

There can be other technologies, different from those developed by S5, that close starshade technology gaps. One example of this is Palacios et al.,[14] who showed another method of sensing starshade position. Palacios et al. also sensed the starshade shadow in the telescope pupil plane at a wavelength outside the starshade stopband. Rather than match the image to a library of images, they fit a Bessel function to the spot of Arago to find the starshade offset. This method also provides sufficient precision for SRM and HabEx.

2.3 *Deployment Accuracy and Shape Stability*

The S5 baseline starshade mechanical architecture is based upon large deployable structure concepts with flight heritage. The opaque inner disk of the starshade, to which the petals are attached, is based upon the Astromesh antenna,[15] which has been flown on numerous spacecraft, including the Soil Moisture Active Passive mission. The Astromesh antenna rim consists of a few dozen truss bays that connect to one another through hinges. The structure can be folded bay-by-bay into a diameter several times smaller than the full antenna. In the S5 starshade, a single flexible petal is attached to each bay by a hinge mechanism. The petals can be collectively wrapped around the folded inner disk thus making the entire starshade small enough to fit into a currently available launch vehicle fairing. After launch, the petals are unwrapped, and the inner disk then unfolded, to deploy the starshade into its operational shape. This concept is described in much greater detail in the companion article by Arya et al.[5]

This deployable architecture has the virtue of being testable for shape accuracy on the ground prior to launch. It also conveniently divides the functionality for the two deployment accuracy and shape stability technologies between the starshade's two main mechanical subsystems. The petal assemblies are responsible for holding the shape that realizes the transmission profile that provides the starshade's deep shadow. The inner disk assembly is responsible for deploying the petals to their correct locations and orientations around the starshade circumference.

Arya et al.[5] present results of recent tests of the deployment accuracy of inner disk and petal prototypes recently built and tested by S5. These prototypes are low fidelity versions of the flight hardware, in that they include only the elements critical for maintaining the starshade shape. These tests showed that the prototype articles meet the performance requirements of S5. Future work within S5 will demonstrate performance within requirements using prototypes with all flight features (e.g., the panels required for starshade opacity).

S5 is also currently concluding a set of tests of the thermal stability of starshade petals and inner disk subassemblies. Thermal stability during observations in flight is another requirement for these technologies to reach TRL5. These results will be presented in a future publication.

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