NASA’s starshade technology development activity

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ABSTRACT

The Astro2020 report recommended that NASA’s next flagship have direct imaging of rocky, Earthlike exoplanets as its core science mission. At present, the starshade is the only high contrast imaging technique that has demonstrated broadband contrast at levels suitable for imaging exo-Earths in the laboratory. A starshade is an occulter positioned to cast a shadow of an exoplanet’s host star onto the telescope aperture, and narrow enough that the nearby exoplanet remains visible to the telescope. The starshade has a precise shape tailored to suppress diffraction of the starlight into the shadow. Starshade-based observations also have other advantages compared to coronagraphic observations. These include: no effective limit to the outer working angle, higher throughput for the exoplanet light, dramatically simpler requirements on the telescope optics, and the ability to provide high contrast at ultraviolet wavelengths. These advantages come at the price of needing a separate spacecraft to fly the starshade in formation with the telescope, and the consequent costs in fuel and time required for stationkeeping and re-targeting. We describe work being done to mature starshade technology to technology readiness level 5 (TRL 5) in NASA’s S5 activity. This work includes optical measurements of a starshade’s ability to suppress light at levels required for a flagship mission, laboratory demonstrations of position sensing and control methods for starshade formation flying, and manufacture and test of flight-like starshade mechanical assemblies that can deploy accurately and stably to the precise shape required for starlight suppression in space.

Keywords: starshades, exoplanets, high contrast imaging, technology

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1. INTRODUCTION

The 2020 Decadal Survey on Astronomy and Astrophysics (Astro2020)¹ recommended that NASA’s next astrophysics flagship mission have the scientific goal of directly observing and
measuring atmospheric spectra for ∼25 potentially habitable exoplanets. 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, casting a deep shadow that prevents 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. The exoplanet would then still be impossible to see in the resulting glare. A disk that varies from perfectly opaque at its center to perfectly transmitting at its circumference can apodize the starshade’s diffraction pattern, dramatically reducing the intensity in the spot of Arago if the variation of transmittance with radius is suitably chosen. It is more practical for a starshade to approximate a purely radial
variation of transmittance by having a flower-like shape petals around its circumference. The petals are shaped so the fraction of the circumference in the gaps between petals provides the desired radial variation of transmittance. With enough petals (typically two dozen or so), this binary mask approximation yields essentially the same shadow as the azimuthally symmetric ideal. A description of starshade apodization has been given by Cash.²

A thorough summary of the historical development and status of starshade technology development as of early 2021 can be found in a series of articles published in a special section of the Journal of Astronomical Telescopes, Instruments, and Systems.³ This article describes the status and recent advances in starshade technology development since those articles were published.

2. TECHNOLOGY GAPS TO STARSHADE MISSIONS

NASA uses a technology readiness level (TRL) scale to describe the maturity of diverse space mission technologies in a consistent manner.⁴ 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 flightlike test articles tested in increasingly flightlike environments. 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 Astrophysics Division has developed a list of technology gaps for astrophysics missions, including exoplanet science missions, which
can be found at its Astrophysics Technology Development website. The Astrophysics gap list currently lists two technology gaps for starshade missions: starlight suppression, and deployment accuracy and shape stability.

Since 2018, NASA has developed starshade technology within the Starshade to TRL 5 (S5) activity. S5 has a directed budget, formal milestones, dedicated management, and an enhanced systems engineering function all described in the S5 Technology Development Plan. NASA’s Exoplanet Exploration Program (ExEP) maintains an external review board, called the Exoplanet Technology Assessment Committee (ExoTAC), to decide when ExEP technology efforts meet their development milestones. The ExoTAC reviews S5 milestones and makes the determination when a starshade technology has reached TRL5.

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.

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. S5 is developing 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.

Previously, the ExEP maintained a distinct technology gap list specifically for exoplanet missions. That prior gap list included a third starshade technology gap: formation flying technology. This gap is currently considered to be closed by milestone demonstrations previously reported by S5 and so does not appear in the Astrophysics gap list.

The readiness level of a technology is evaluated with respect to the specific mission in which it will be used. S5 was begun with the working assumption that the Starshade Rendezvous Mission (SRM) would be NASA’s first starshade mission. 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. The main difference between the two missions for starshade technology development is that at 52 meters diameter the HabEx starshade is twice as large as the 26 meter diameter 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 as well as for SRM.

The exoplanet direct imaging flagship mission recommended by Astro2020 is neither SRM nor HabEx, but an even larger telescope with \( \sim 6 \) meter aperture. The requirements imposed on starshade performance for such a mission are only now being considered, but it is possible that they will differ from the requirements that were assumed by S5.
NASA has decided to discontinue funding its directed starshade technology development starting in fiscal year 2023, and has directed the S5 activity to advance starshade technology to the extent possible with existing funds. NASA intends to fund future starshade technology development through competed Technology Development for Exoplanet Missions (TDEM) grants.

2.1 Starlight Suppression

Experiments by Harness et al. in a 77-meter long testbed at Princeton have demonstrated that small-scale starshade masks achieve $10^{-10}$ contrast at their inner working angle over a 10% optical bandwidth.\textsuperscript{11} As of this writing, this is the only laboratory demonstration of high contrast imaging at levels suitable for imaging exo-Earths without a post-processing gain.

Since then, the S5 team has tested the optical performance of a series of starshade masks that incorporate deliberate errors. Some masks have flaws such as an outward displacement of part of the petal edge built into individual petals, thus testing the effects of petal shape errors. Other masks have some or all of the petals displaced outward as a whole from their nominal locations, thus testing the effects of petal position errors. One mask has both shape and position errors, allowing the interaction between errors to be probed. These experiments have been concluded, and the Princeton testbed is being decommissioned. Generally, errors in petal shape cause changes in contrast that are predictable by starshade contrast models to within 25%, while errors in petal position cause changes in contrast that are predictable to within 100%. The petal shape errors are particularly difficult to distinguish from vector diffraction effects that become significant due to the very small scale of the testbed starshade masks compared to flight
sizes. A companion article in this proceeding by Shaklan et al. describes these results in further detail.

The exoplanet direct imaging mission recommended by Astro2020 would likely operate at the Sun-Earth L2 point, or in an Earth-trailing orbit, 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 back side of the starshade and ensuring that no features on the telescope-facing side protrude into the sunlight. The possibility remains that sunlight can scatter from features on the Sun-facing side of the starshade, to features on the telescope-facing side of the starshade, and then into the telescope itself. These multiple-reflection paths for Sunlight to reach the telescope require careful engineering of the starshade structure, and the use of low reflectivity materials wherever possible, but they are not seen as requiring a new technology. Reducing 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, is an identified technology in the Astrophysics technology gap list. Shaklan et al. 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 because their very sharp radii of curvature minimizes the available surface area that can directly reflect sunlight into the telescope. Even so, the solar glint is still expected to be a relatively bright feature in a starshade image. McKeithen et al. describe the development and test of antireflecting coatings applied to these edges that have the potential to reduce the
solar glint several times further. There is also work being done to incorporate the amorphous metal edges into starshade petals with the correct shapes to meet the contrast requirements and the durability to survive launch and operational environments. A companion article in this proceeding by McKeithen et al. describes the work done over the past year on these issues.

2.2 Deployment Accuracy and Shape Stability

The S5 baseline starshade mechanical architecture is based upon large deployable structure concepts with flight heritage, and is described in detail by Arya et al. The opaque inner disk of the starshade, to which the petals are attached, is based upon the Astromesh antenna, 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 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.

In the past year, S5 has demonstrated that the petals and inner disk subassemblies meet their requirements for thermal stability. The starshade will be illuminated by the Sun from different angles when observing different stars, and it will be hotter when it is closer to facing the Sun directly. The starshade shape must be relatively stable against these changes in temperature if it is to maintain good optical contrast. Strictly speaking, it is not necessary for the starshade dimensions to be perfectly fixed. If the starshade expands or contracts uniformly without changing its overall shape, the contrast variation will be minimal. In practice, it is necessary that the relative change in the width of the petals be matched by the relative change in the width of the inner disk.

Figure 1 shows a prototype petal of ~4 meter length resting upon supports in a hot/cold box that was use to vary its temperature between ±50 degrees Centigrade. (The lid of the box has been removed for the photo.) Displacement measurement interferometers (DMI) and retroreflectors were mounted at several locations to measure changes in the petal width as a function of temperature at several locations along its length. DMIs also measured the thermoeelastic deformation of the petal’s length and from one end of its base to its tip (‘shear’). Some of these DMIs and retroreflectors have been labeled in Figure 1.

Figure 2 shows the measured length changes at +50 degrees Centigrade, along with the predictions of a finite element model of the petal. The agreement between model and data is quite good, and when extrapolated to the full 8 meter flight length the overall change in petal dimensions is well within requirements for all temperatures we tested, with an allowable
growth of 88%. The large deformations seen between some of the petal’s battens were found to be caused by thermally induced moments in the epoxied joints connecting the battens to the petal’s edge. A detailed report on this experiment is available at the ExEP’s web site.\textsuperscript{16} Detailed investigations of creep in petals subjected to long term storage in the furled state have showed that petal width changes due to storage are also well within requirements.\textsuperscript{17}

At 10 meters in diameter, the inner disk is too large for thermal deformation testing, given our resources. S5 has instead measured the thermoelastic deformations of subassemblies of one of the perimeter truss bays from the inner disk. The perimeter truss bays and their interfaces with one another are the primary drivers of the inner disk size. (See Figure 3.) We measured the thermoelastic deformations of the longeron and node assembly and input the data into a finite element model of the truss bay to generate a prediction of the truss bay length change vs. temperature. This could then be compared to the width change of the petal.

Figure 4 shows how much the truss bay length is expected to vary with temperature, given our measurements of its subassemblies. Note that the truss bay has been designed to vary with temperature by an amount that is commensurate with the petal thermal changes in width. This is made evident in Figure 5, which plots both design and measured performance relative to the petal performance. It is evident that the measured truss bay performance meets the requirements with nearly 100% margin. A detailed report on this experiment is also available at the ExEP’s web site.\textsuperscript{18}
2.3 Formation Sensing and Control

As mentioned already, the formation flying technology gap was closed by the work of Bottom et al. and Flinois et al., and as a result no gap associated with formation flying appears in the Astrophysics technology gap list. Advances in this technology continue nevertheless. Martin and Flinois developed methods to simultaneously sense the starshade position and the telescope pointing relative to the line of sight to the star. These methods use phase dimples or vortices in the pickoff to the telescope’s low order wavefront sensor to disentangle the telescope pointing from the starshade position in the telescope’s pupil image, and sometimes included neural network derived position and pointing algorithms that can be implemented in spacecraft in a computationally efficient way. Anthony Harness’s team at Princeton demonstrated closed loop control of starshade mask position in the Princeton testbed, also with a computationally efficient neural network based algorithm.

2.4 Starshade Data Challenge

In 2020, the S5 project launched a data challenge with the goal of learning how precisely exoplanets could be identified in artificially generated starshade images. These images were generated using the SISTER image simulation tool, and included realistic models of starshade contrast and positioning, zodiacal and exozodiacal light, and solar glint. Two teams won a competition to be funded to participate in the challenge, one led by Brian Dunne at Quartus Engineering and the other led by Angelle Tanner at Mississippi State University. This data challenge has just concluded, with both teams submitting their final reports to S5. S5 is evaluating the results and will report on them in a future publication.
Disclosures

The author has no relevant financial interests in the manuscript and no other potential conflicts of interest to disclose.

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Figure 1. Prototype petal in hot/cold box for thermoelastic deformation measurements.
Figure 2. Thermal expansion of the prototype petal at 50 degrees Centigrade. The red dots show the measurements and the green squares are predictions of a finite element model of the petal.
Figure 3. Starshade inner disk and perimeter truss bay. The longeron and node assembly are shown.
Figure 4. Absolute length change of the truss bay with temperature. Note that the temperature scale has been expressed in terms of solar illumination angle.
Figure 5. Truss bay length change with temperature, relative to ideal set by expected petal width change. Note that the temperature scale has been expressed in terms of solar illumination angle.