In-Space Assembly of a Starshade as an External Occulter for Direct Exoplanet Observations

A Space Mission Astro2020 APC White Paper for Enabling Exoplanet Characterization

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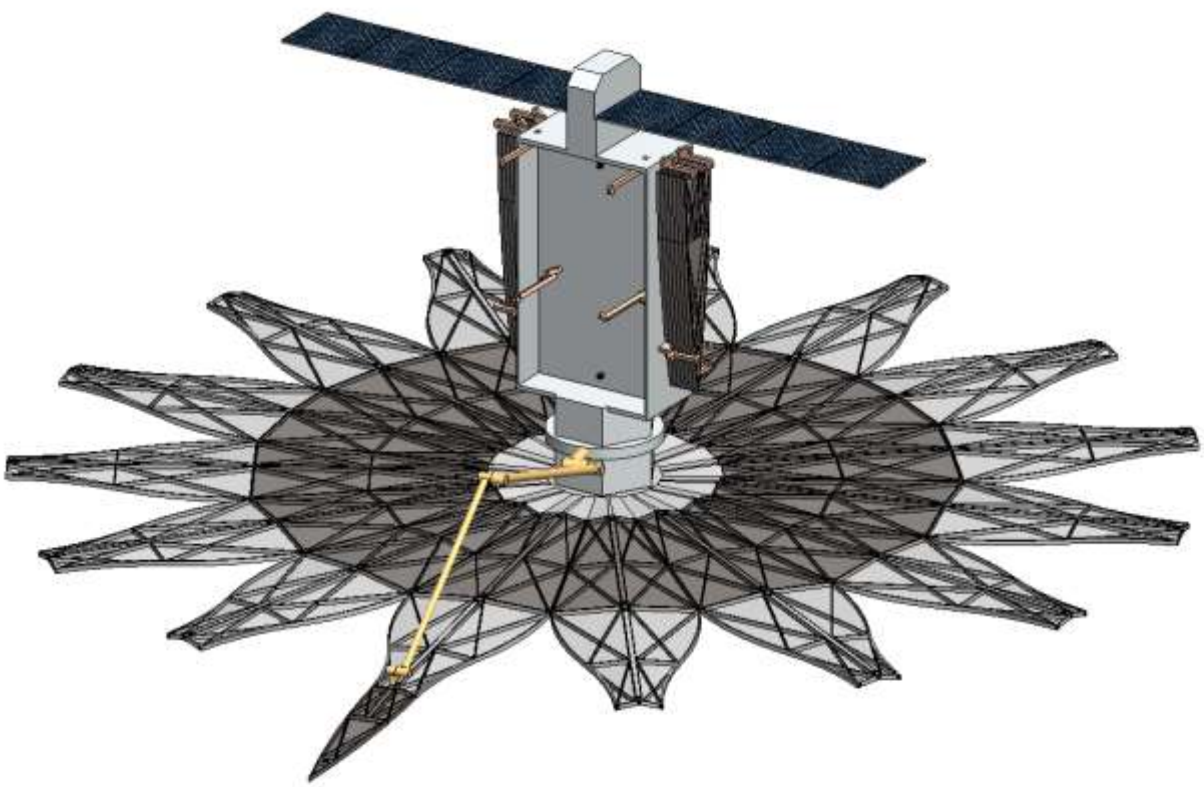

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John Grunsfeld (Endless Frontier Associates, NASA GSFC Emeritus), Matt Greenhouse (NASA/GSFC), Rudranarayan Mukherjee (JPL/Caltech)

Introduction

The science case for space-based telescopic direct imaging in reflected light to spectroscopically characterize planets around Sun-like stars is well established[1]. Use of an external occulter, such as a "starshade," has been studied in much detail and great progress has been made in designing mission concepts using this technology. For missions such as WFIRST, and reference studies for future observatories such as HABEX and LUVIOR, the use of a starshade for exoplanet characterization can be transformative. Following the recommendations of the Astro2010 Decadal Survey NASA has invested in the advancement of the starshade technology with substantial results.

The technical challenges of producing a starshade with the required dimensional characteristics, stability, and optical properties have been met with innovative solutions and much progress has been made. A recent Probe Study Report[2] developed to help inform the Astro2020 Decadal Survey describes the results on an in-depth analysis of creating a starshade mission (Starshade Rendezvous Probe) capable of meeting the technical challenges to fly with the WFIRST mission. The report details the current status of the technology gaps for starshade development, risk assessment, mission architecture, cost and schedule. In Table 6-1 from the report is reproduced the Key Performance Parameters for the Starshade Rendezvous Probe for their "S5" activity[2,3] as an example of the challenges that are successfully being addressed.

TABLE 6-1. Key performance parameters.

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

The essential message from the report is that building a starshade compatible with WFIRST and potential future observatories on the scale of HABEX is viable given resources for technology maturation and in the cost range of a Probe-class mission (defined as ≈$1B). Such a starshade would be approximately 26-meters in diameter for WFIRST[2].

This white paper describes an alternate method of achieving a starshade with the required performance and mission parameters at potentially a much-reduced cost, and at lower risk. *To be clear, the concept produced here is preliminary and reflects the initial evaluations of the* *approach.* If the results of the Astro2020 Decadal Survey recommend the development of a starshade to support the science objectives of exoplanet spectroscopic characterization we suggest that NASA undertake a study, to evaluate the implementation of the ideas presented here, for comparison with the funded and very detailed and innovative Rendezvous Probe Study.

The concept presented below is to construct a full scale starshade on the ground using rigid panels to the specified precision and accuracy using currently certified aerospace grade materials, in segments that can be disassembled and packaged for reassembly in space by simple robotics. This approach is motivated by the desire to produce a starshade using current TRL-9 materials and technology, a design that is inherently stable, highly resilient to launch loads, vibration, and acoustics, low cost to produce, and scalable to larger starshade diameters. The starshade as a payload would be attached to a spacecraft with similar characteristics to the Starshade Rendezvous Probe concept, but with the addition of a simple robotic arm and the associated avionics.

The Concept

Imagine if you could laser-cut a starshade out of rib-reinforced aerospace grade carbon composite sheet in one large piece on a technical "flat" floor. It would have the exact shape required to within cutting tolerances (far better than required), and the petals would have stiffness against flexing in the direction that changes the optical properties. Then imagine cutting this starshade into pieces, petals and pie shaped segments, match drilling them to their original mates. Then taking these pieces and packing them into a rocket, to be reassembled in-space back into the original starshade. This is the notional concept or inspiration of the self-assembled starshade.

The application of this idea to an implementable starshade preserves the stiffness, shape control, precise and accurate metrology of the notional concept. The elements of a practical in-space assembled starshade are the following: a stiff circular base launched as a one-piece assembly attached to the spacecraft, and a logistics carrier holding the element pieces, identical, but serialized (only goes to one receptor site) circular section segments, petal bodies, and petal tips.

The entire starshade, once manufactured, can be assembled on the ground on a technical flat floor (a number exist of the scale required), so that the exact shape can be measured, and if required the pieces can be shimmed to the exact shape required. As described below, once the shape is set, that same shape will be reproduced in-space with tolerances well below that required for the optical performance. This is ensured using standard and current manufacturing processes—no new inventions are required. This more than satisfies the Petal Shape and Petal Position requirements outlined in Table 6-1 above.

The spacecraft has a simple robotic arm which picks and places the petals and tips together once on orbit. The robotic arm is a small non-dexterous arm similar to that flown on the Space

Shuttle, International Space Station, Japanese Experiment Module, proven on the Orbital Express Mission in the early 2000's, and designed into several current space robotics programs for launch in the next several years, including the NASA RESTORE-L mission which has 2 such arms (launch in ~2022). The robotic software and control required is about the simplest that is imaginable, requiring only several simple trajectories for the repetitive "pick and place" operations. Post assembly the robotic arm remains on the spacecraft, stowed. In the event of a micrometeorite puncture of a petal, the arm in principle could apply a patch (heritage to Space Shuttle thermal insulation repair, and Hubble Space Telescope multi-layer insulation repair).

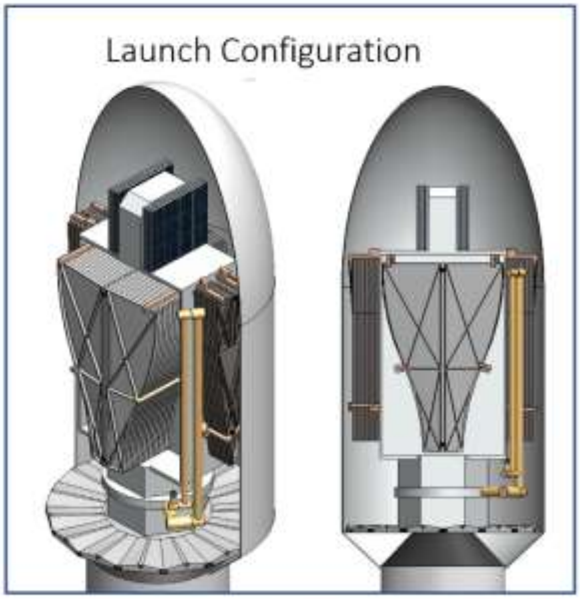
The circular sections, petals, and tips themselves are to be constructed of rib reinforced carbon-fiber composites for stiffness, thermal stability and overall shape control. If required they can be light weighted by cutting out sections not required for overall stiffness and covered in multi-layer insulation for thermal stability. The interfaces between the piece parts have simple kinematic mounts and space-proven heritage latching, as used on Hubble and other orbital programs. The kinematic mounts constrain the petals to register to each other as precisely as they were mounted and adjusted on the ground.

Launch would be on a SpaceX Falcon-9 class vehicle. Following commissioning of the spacecraft, the assembly would take place using supervised autonomy while in cruise to the starshade destination. An estimates of assembly time assuming no anomalies is measured in days. Once assembled the carrier structure could be jettisoned. No special requirements are needed on the ground beyond any other deep space science mission. Communications would be through the Deep Space Network, with only modest telemetry requirements.

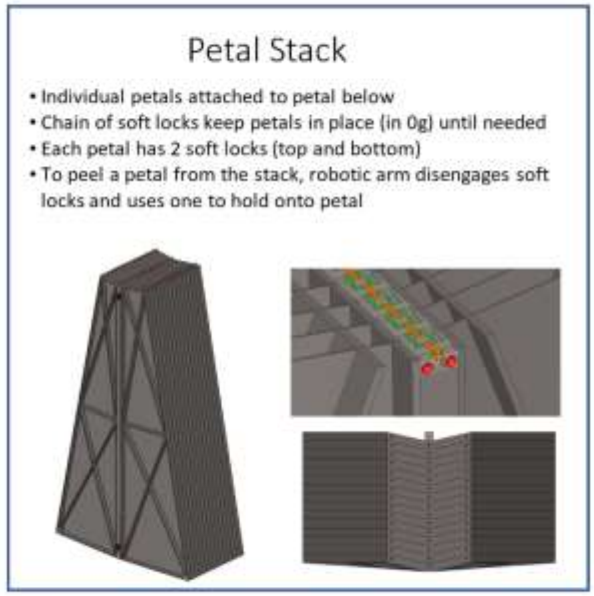
The beauty of this concept is that it uses technology that has simple mechanical interfaces, manufacturing methods, and robotics, that have all been developed and deployed in space, and as such are TRL-9.

The elements which are not flight-proven, are the edge treatments of the petals and tips, and the spacecraft formation flying technology. These are in the technology maturation plan for starshades as is well described in the Starshade Rendezvous Probe study and in the technology roadmap for the NASA Exoplanet Program.

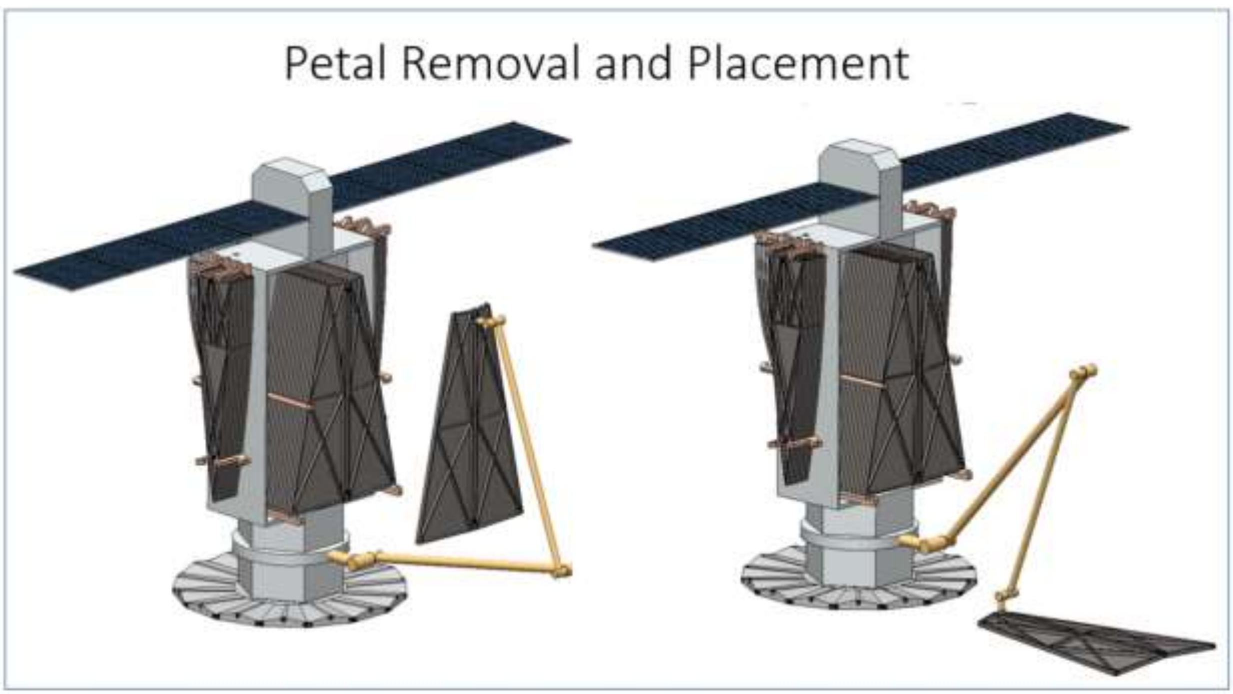
The following series of images show the basic concept of the in-space assembled starshade from a small NASA/JPL/Endless Frontier Associates effort to assess the viability of the approach.



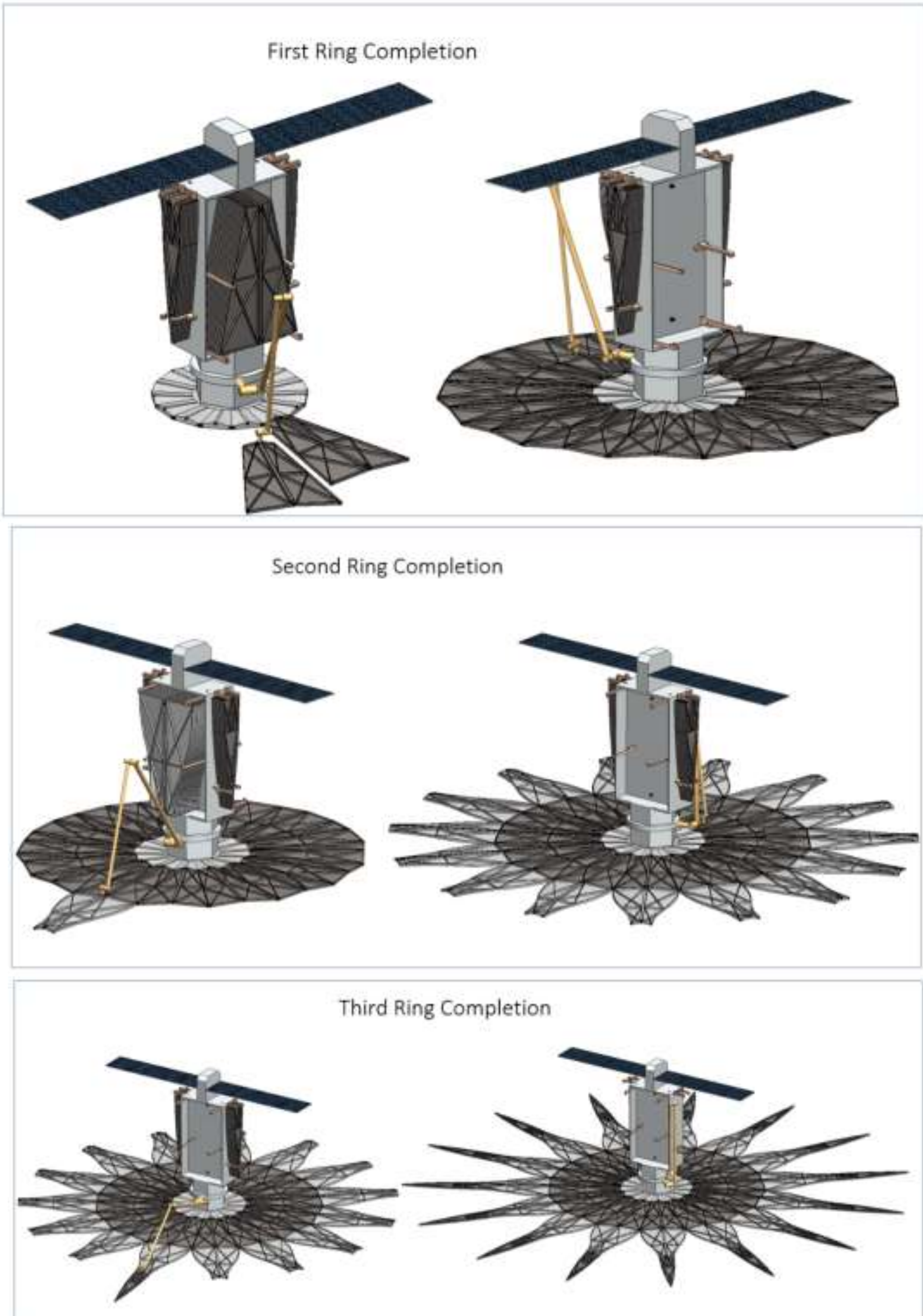
1 Launch Configuration in Fairing. Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech1



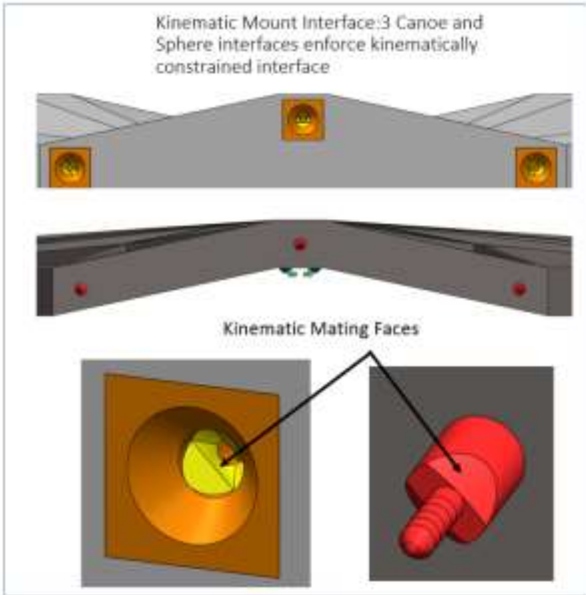
2 Launch stowage and lock configuration. Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech



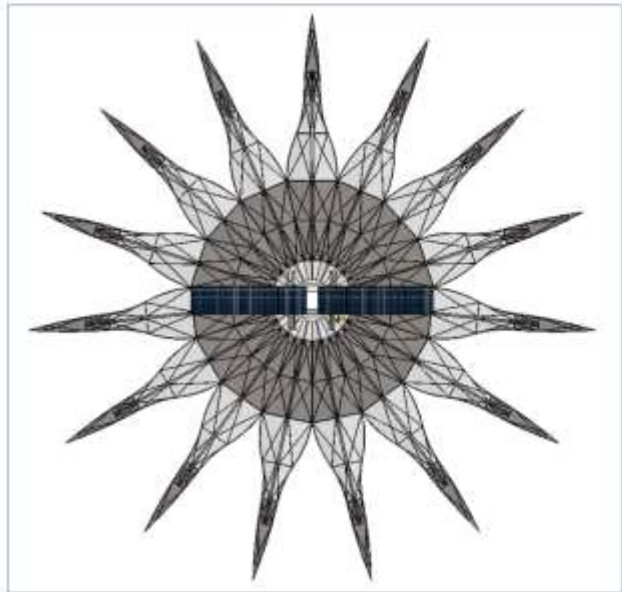
3 Once spacecraft is deployed assembly begins with circular section. Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech



4 Starshade assembly sequence, first, second, and third rings to completion. Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech



5 Example of a kinematic mount interface. Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech


6 Completed Starshade. . Credit: Spencer Backus, Dane Schoelen and Rudra Mukherjee, NASA/JPL Caltech

Technology Drivers

The principle new technologies required to implement this approach are the optical quality edge treatments of the starshade petals, and the formation flying of the spacecraft with the space telescope.

The development of the amorphous metallic edges by NASA/JPL as described in the Starshade Rendezvous Probe is currently the most likely solution to any starshade project. The same technology development is required to develop manufacturing, testing and integration of the edges for any starshade project.

The same is true for the guidance, navigation and control of the spacecraft with respect to the telescope. A sound engineering approach is already underway to solve and demonstrate formation flying at the required specifications.

By utilizing principally TRL-9 designs, and rigid starshade elements, what is <u>not</u> required is extensive development and testing of the elegant, but complex origami unfolding of flexible elements in the currently studied starshade designs, including petal unfurling and perimeter deployment systems. The only moving part in the concept proposed here is the flight proven robotic arm.

Cost and Schedule

Since this is an early concept design, we have not performed a detailed cost estimate at the fidelity of any of the other concepts. A very preliminary costing suggests that a 26-meter design could be developed at substantially lower cost than a full probe class mission including reserves. Since this concept does not require large up-front engineering development, it is ideal for soliciting bids (including firm fixed price) from aerospace and industrial contractors. The deep-space spacecraft, robotics, and other systems have recent analogs in a variety of programs including Discovery, Explorers, and commercial spacecraft. In a competitive environment this can keep the cost down significantly compared to a cold-start large development program. The most likely result of a cost study would be an estimated cost for the mission somewhere between the low to mid-range of the “Medium” cost class for Astro2020, but quite a bit lower than the Starshade Rendezvous Probe estimate. Only by doing the study can this be validated.

Often of concern is the infrastructure to support the robotics. In this concept the only robotics required is the robotic arm, controller, sensors, and software which reside on the spacecraft. All the components of the robotic system have been constructed for other space programs, and as such are acquisition items. For example, the estimate for the cost of the robotic arm is approximately $10M.

By using mature technologies and simple construction methods, such a starshade and spacecraft can be produced in a short project development cycle, driven by the spacecraft and not the starshade manufacturing (other than the development required for the edge treatments). It is conceivable that an in-space self-assembled starshade could be ready to launch in the same timeframe as the WFIRST telescope.

If budget were available, the advantage of a lower cost option is that 2 starshades could be produced and launched which significantly increases the efficiency of observations allowing one to be used for observations, which the second maneuvers to the next observing location.

Benefits

The primary benefit of this approach is that it uses simple mature technology to achieve native stiffness, shape control, and precise positioning. This alleviates many of the concerns of the deployable designs, which must be constructed and tested using gravity offload mechanisms, complex analysis of gravity loading, and extensive testing to ensure that the in-space shape will meet requirements.

One of the strong benefits of the rigid design, and in-space assembly is that the storage of the panels and petal parts in the launch vehicle has higher structural integrity than the individual piece parts. This provides a ruggedization that will protect the pieces from the rigors of launch loads, vibration and acoustics—a major issue in the deployable designs as we’ve learned from the James Webb Space Telescope. This translates into less unique testing, verification and validation, which translates into substantially lower cost and shorter schedules when considering assembly, integration, and test, and launch integration and operations.

The rigid panel technology is used in manifold aerospace applications, and due to the replication of large numbers of identical segments, petals, and tips, allows an economy of scale, well within the capabilities of numerous manufacturers. This translates into lower cost, lower risk, and faster schedules, than custom manufacturing of delicate parts.

Once the starshade is assembled and operational, the robotic arm could be used for micrometeorite repairs, and if desired, to grapple a simple refueling tanker to extend the mission life. This technology has been proven on the International Space Station with the RRM series of experiments and will be used to refuel Landsat-7 by the RESTORE-L mission.

While this white paper describes a starshade concept for WFIRST, the basic concept can be almost arbitrarily scaled to larger diameters. There is a limit for current robotic arm lengths, but for larger diameters, the robotic arms are designed to "walk" out to allow extension to more distal radii. This does require powered grapple points, also a TRL-9 technology, but adds extra mass and some complexity to the structure. Still in the realm of straightforward engineering. Thus, demonstrating the in-space assembly of a starshade of 26-meters for WFIRST would enable a larger starshade deployment for a future large aperture exoplanet observatory.

Other concepts have been proposed for in-space assembly for astrophysics including in a white paper for in-space assembly of large space telescopes for Astro2020.[4] In-space assembly of a starshade is a straightforward engineering exercise. The experience gained in actualizing the in-space assembly of a starshade would provide valuable insight into the more complex problem of designing and implementing the in-space assembly of an observatory as described in the referenced white paper, and the In-Space Servicing and Assembly website of the NASA Exoplanet Program[5].

Conclusion

The use of a starshade as an external occulter is a highly leveraged method of enabling spectroscopic characterization of temperate exoplanets around nearby sun-like stars. The scientific yield of future observatories can be substantially increased by the addition of a starshade. We suggest that a lower-cost, and lower-risk option to achieve the goal of a starshade able to support WFIRST, and future observatories recommended by the Astro2020 Decadal Survey, *may* be a starshade constructed on the ground, validated, and then packed and shipped to orbit for reassembly. The purpose of this white paper is to motivate the study of such an option.

Recommendation: NASA should undertake a detailed study to determine the technical performance parameters, mission architecture, cost, risk, and schedule, for a ground produced rigid starshade, constructed in a modular architecture, competitively procured, launched, and reassembled in-space using simple robotic assembly[3].

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References:

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