Advances in Starshade Technology Readiness for an Exoplanet Characterizing Science Mission in the 2020's

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ABSTRACT

The discovery of thousands of exoplanets is generating increasing interest in the direct imaging and characterization of these planets. Starshade, an external occulter, could fly in formation between a telescope and distant star, blocking out the light from the star, and enabling us to focus on the light of any orbiting planets. Recent technology developments in coordination with system level design, has added much needed detail to define the technology requirements for a science mission that could launch in the 2020's. This paper addresses the mechanical architecture, the successful efforts to date, the current state of design for the mechanical system, and upcoming technology efforts.

Keywords: starshade, occulter, high contrast imaging, WFIRST

1. INTRODUCTION & BACKGROUND

Starshade is a space-based concept for the purpose of directly imaging exoplanets. The starshade external occulter would fly in formation with a companion telescope, blocking the light of a distant star, allowing the telescope to focus on the light of its orbiting planets. Because the starshade is an external occulter, the requirements on the telescope to achieve contrast ratios on the order of 10^{10} are greatly reduced. These reduced requirements on the telescope come at the cost of formation flying a precision shaped occulter structure of 20 plus meters in diameter.

As shown in Figure 1, the starshade occults the light before it enters the telescope, and therefore requires a separation distance of 25-50 Mm from the telescope, depending on the mission parameters. The inner working angle (IWA) for any given mission is, in part, determined by the size of the starshade and separation between the starshade and telescope. The smaller the inner working angle, the closer into the star the telescope can image. Because the starshade blocks the light before it enters the telescope, the starshade must be formation flown with lateral precision on the order of +/-1m in order to maintain the shadow on the telescope. Note this requirement is based on oversizing the shadow created by the starshade so as to create a lateral tolerance. The axial position of the starshade is much looser because this motion only serves to slightly change the apparent size of the starshade from the perspective of the telescope, and thus has a tolerance on the order of +/- 250 km.

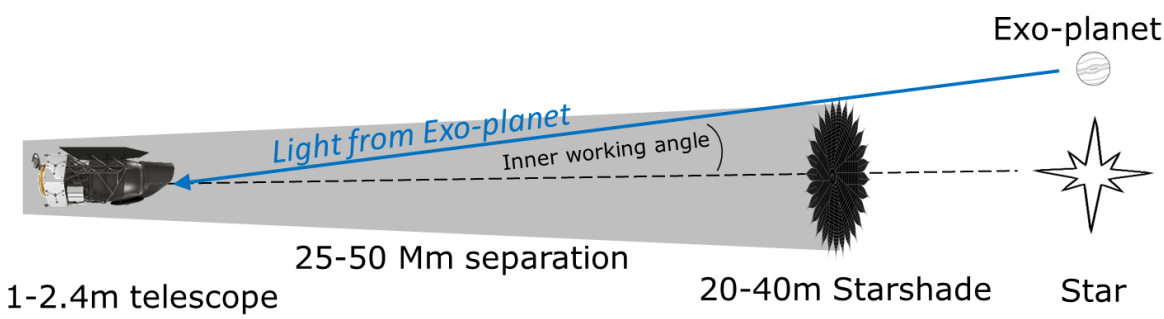

Figure 1. Starshade formation flies between a telescope and star, casting a deep shadow

2. MECHANICAL ARCHITECTURE OVERVIEW

Early technology efforts funded by NASA under the Technology Development for Exoplanet Missions, or TDEM, demonstrated "tall tent pole" precision mechanical requirements for a starshade mission and defined a conceptual mechanical architecture[2, 3, 4]. The architecture defined an inner disk with "petals" appended to the structure to control diffraction of the starlight. Figure 2 shows an updated version of this architecture as defined in the NASA Exo-S report[1].

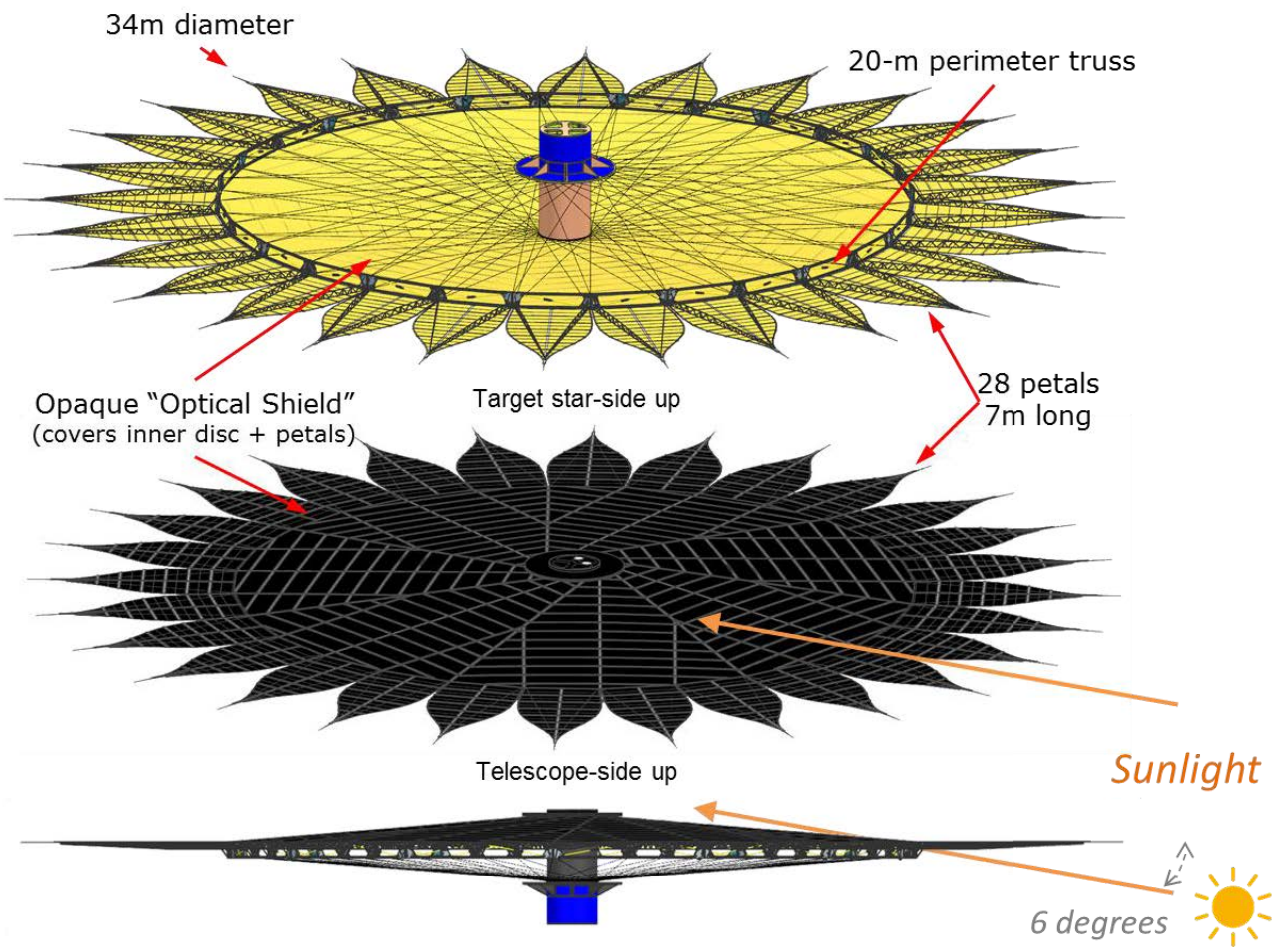

Figure 2. Mechanical architecture as outline in the Exo-S report[1]

The inner disk of this architecture is realized via a deployable carbon fiber perimeter truss that draws on the architecture of deployable antennas such as the Northrup Grumman Astromesh Antenna and can be seen in Figure 2. The perimeter truss is a series of repeated truss "bays" that deploy via a deployment cable that serpentines the perimeter truss and is spooled in by a motor, forcing the bays to deploy as shown in steps 3-5 of Figure 3. Once deployed, the spokes elongate and tension, holding the perimeter truss ring in compression, much like a bicycle wheel. The truss is also responsible for pulling out the inner disk optical shield. Note that during this portion of the deployment, the petal deployment is passive; in other words, the truss carries the petals from the vertical and radial position to the horizontal and planar deployed position without any articulation of the petal with respect to its attachment point on the truss.

The petals are loosely analogous to the ribs of the Lockheed Martin radial wrapped rib antenna and as such are designed to be thin so as to wrap (furl) around the stowed inner disk structure as shown in the first three steps of the deployment sequence of Figure 3. The petals then gain out of plane operational stiffness via two deployable ribs that pop up upon

unfurling of the petals. The entire structure is then covered with an "optical shield" comprising multiple layers of black kapton interleaved with foam, leaving only the opaque optical profile of the edge of the starshade.

The basis for this architecture was to meet two driving requirements:

1. Petal profile accuracy requirements of approximately +/-50 microns[3]
2. Petal positional accuracy on the inner disk of approximately +/- 1 mm[4]

Requirement 1 led to a design that structurally maintains the petal optical profile from the initial stowed position until its final deployed state. In other words, the petal is only hinged at its base, from which it is furled around the stowed structure without any further hinging along the shape profile. This translates into a robust design that can be built and measured on the ground to the +/- 50 micron requirement and does not require segmented articulation within the petal. In other words, the petal is not a mechanism, it is a structure. Additionally, while the starshade requires between 16-32 petals, all petals are of the same mechanical design and construction.

Requirement 2 led to infusion of the perimeter truss. Perimeter trusses have been used for decades as a means of deploying precision parabolic antennas meshes that can be stowed into a small cylindrical volume. This tensegrity structure is conveniently facetted around the circumference, easily accommodating the addition of individual petal appendages.

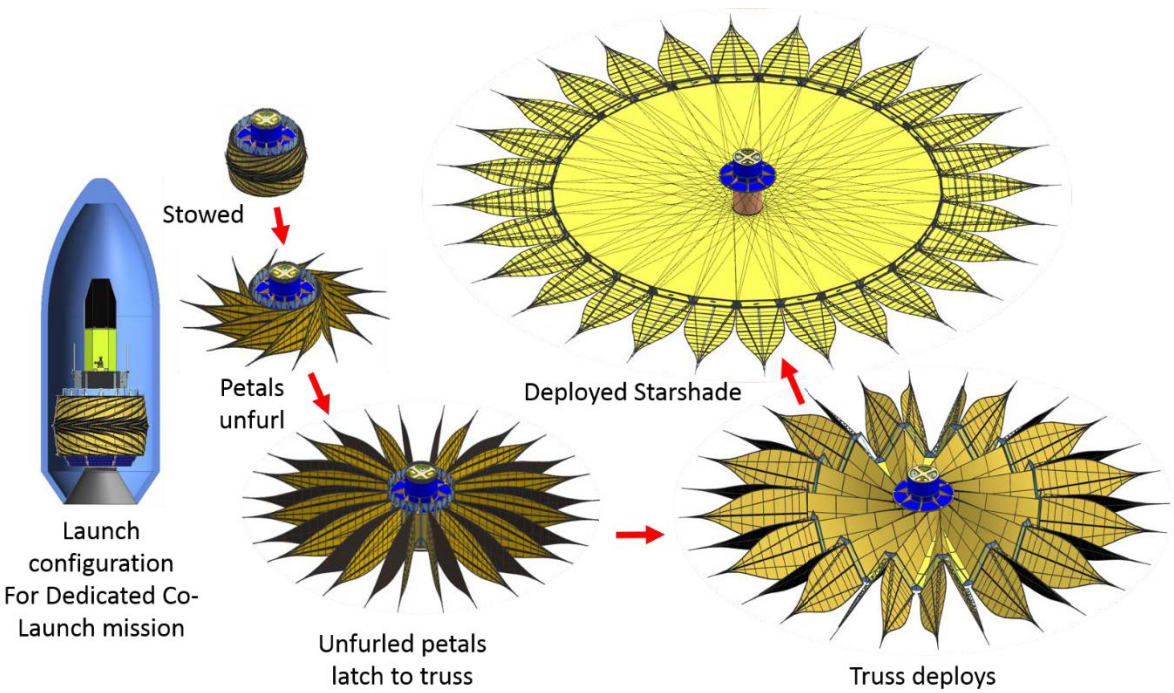

Figure 3. Mechanical deployment architecture as outline in the Exo-S report[1]

3. TECHNOLOGY ACCOMPLISHMENTS

Advances in mechanical system technology have been achieved, in large part, via two NASA funded TDEM awards to principal investigator Jeremy Kasdin of Princeton University, as well as infrastructure funds from the NASA exoplanet

office. These efforts were focused on the two tallest technology gaps and correspond to the two drivers for the mechanical architecture:

1. Demonstrate production of a full-scale starshade petal, using flight-like processes and materials to near-flight tolerances via the "Advancing Technology for Starlight Suppression via an Eternal Occulter[3]"
2. Verify that the deviations of the petal base point from the design circle are repeatedly below the 3-sigma positioning requirement for a 10^{-9} contrast using a sufficient number of deployment to verify the requirements are met with 90% confidence via "Verifying Deployment Tolerances of an External Occulter for Starlight Suppression[4]"

Technology Gap 1:

The first gap, petal profile accuracy, was addressed by the TDEM "Advancing Technology for Starlight Suppression via an Eternal Occulter[3]." The details of this effort and its results will not be repeated here, but rather a summary description of the results and its influence on the mechanical design and technology advancement is important to this discussion.

The starshade architecture was defined early, as described in the overview section of this paper. The initial architecture shown in Figure 4 was defined by this effort and contains details in two important areas, the perimeter truss, which is the basis for gap 2, and the petal, which is addressed by gap 1. The principal technology accomplishment of this effort was to design, build and measure a flight-like, full-scale starshade petal to the near-flight tolerances. Figure 5 shows the as-built detailed petal at the Jet Propulsion Laboratory alongside a summary representation of the as-measured fabrication tolerances achieved through this effort. The as-measured green data points are shown against the 100 micron wide tolerance allocated to the as-manufactured petal profile. This effort showed that a petal of flight-like materials could meet the as-manufactured tolerances required by the starshade. Also worth noting is that the basic architecture for the petal that was defined by this effort has remained, with the current focus being refinement of the details and added definition.

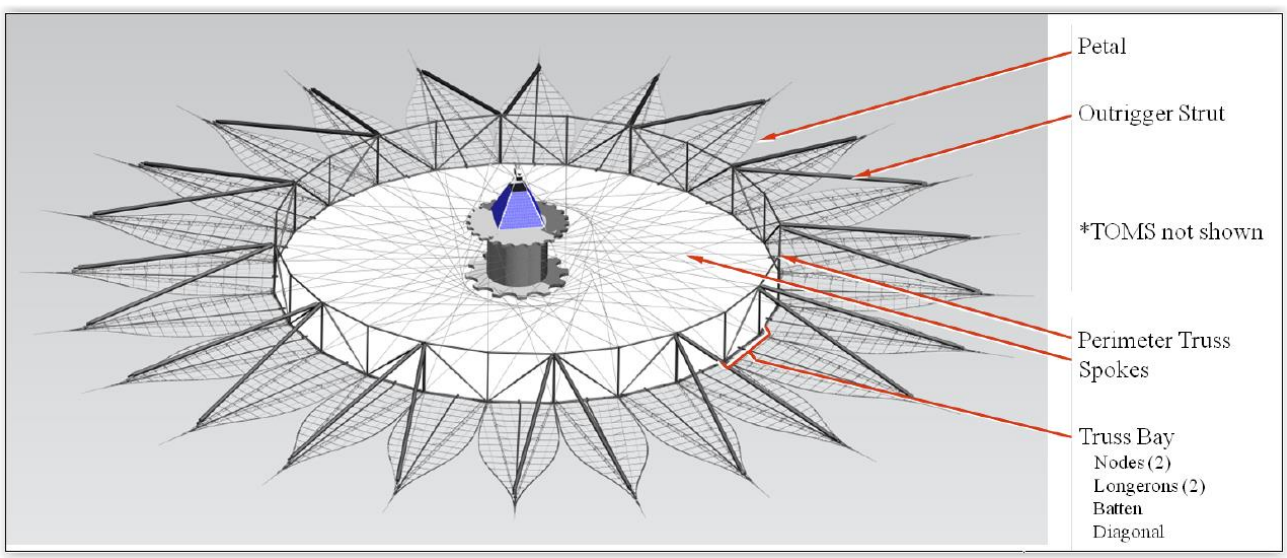

Figure 4. Starshade mechanical design as defined in "Advancing Technology for Starlight Suppression via an Eternal Occulter, Technology Milestone Report[3]"

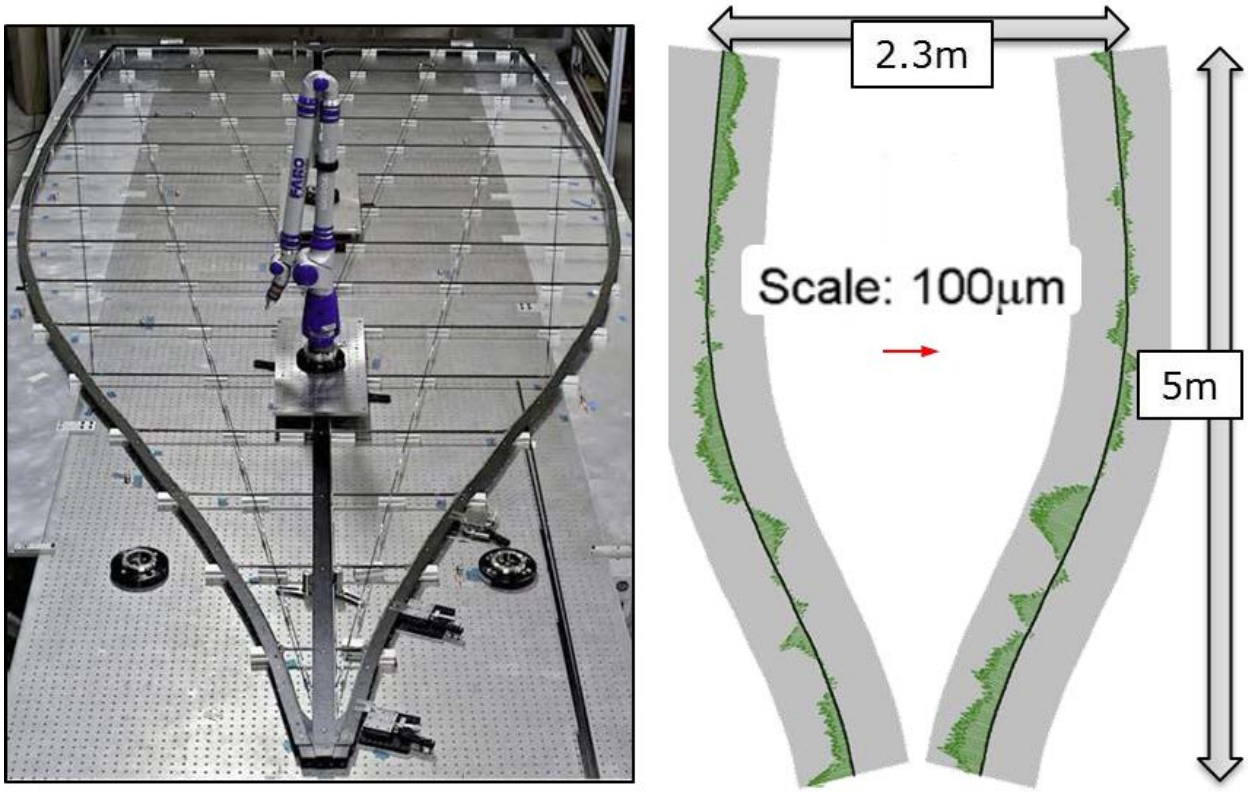

Figure 5. Starshade as-built petal and summary illustration of as-measured mechanical fabrication tolerances per "Advancing Technology for Starlight Suppression via an Eternal Occulter, Technology Milestone Report3"

Technology Gap 2:

The requirement of petal placement was addressed in the TDEM "Verifying Deployment Tolerances of an External Occulter for Starlight Suppression[4]." The details of this effort and its results will not be repeated here, but rather a summary description of the results and its influence on the mechanical design and technology advancement is important to this discussion.

With the starshade architecture established, and manufactured petal tolerance verified, it was necessary to verify petal placement capabilities. In order to achieve this, contributors JPL and Northrup Grumman Astro Aerospace, partnered to modify an existing Astromesh antenna prototype to attach occulter petals and measure their deployment tolerances. Figure 6 below shows the retrofitted Astromesh antenna, along with colored dots representing the many points on the truss measured with a laser tracker. For this demonstration, the milestone was to achieve better than the 3-sigma accuracy requirement of +/-0.95mm for deployed position of the petal roots. The milestone was met with 90% confidence for 15 stow/deploy cycles.

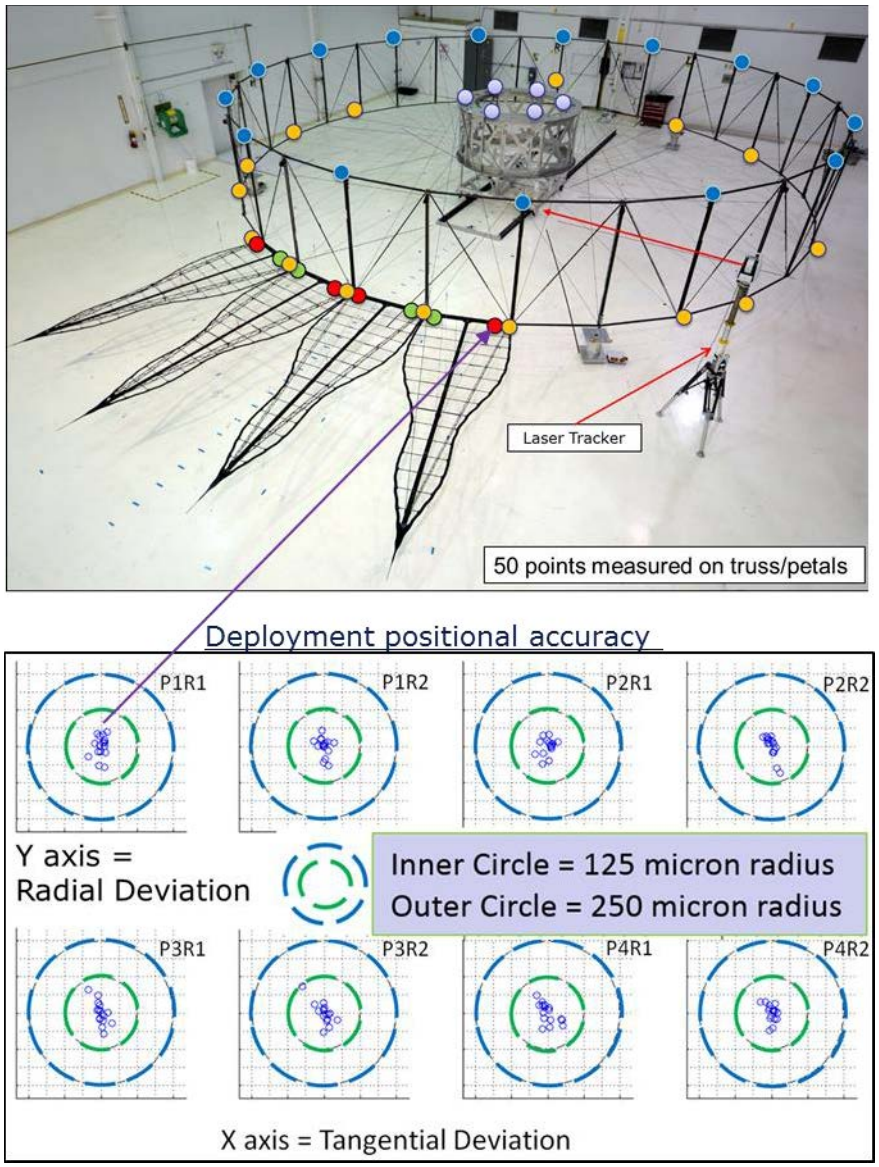

Figure 6. Verification of deployment tolerances using a retrofitted Northrup Grumman Astromesh antenna. Raw deployment data on the right demonstrate petal root position deployment repeatability for four petals attached to the perimeter truss.

Noteworthy for this demonstration is that the Astromesh antenna, while capable of accurately deploying petals to the required tolerances, is not suitable in configuration to properly stow the petals for furling and launch. The TDEM effort was also able to define a perimeter truss design that accomplished this need. Later funding was then able to prove out this design concept with a testbed that demonstrated petal stow and launch configurations along with re-verification of petal deployment tolerances for the new configuration. This design is shown in Figure 7 with fully deployed truss and petals on the bottom and from above shown in the top right. Truss deployment along with the required petal configuration is shown progressing from left to right, fully stowed truss on the left to fully deployed on the right.

This testbed perimeter truss has been the keystone by which the remaining design has developed. Because the perimeter truss is the member to which the petals and the inner disk attach, detailed definition to this system influence and help to define all remaining systems. Also worth noting is that the truss not only serves as the structural foundation for the petals as deployed, but also as the foundation by which the petals are supported for launch. For this additional reason, the testbed truss has greatly influenced and added definition to the mechanical architecture.

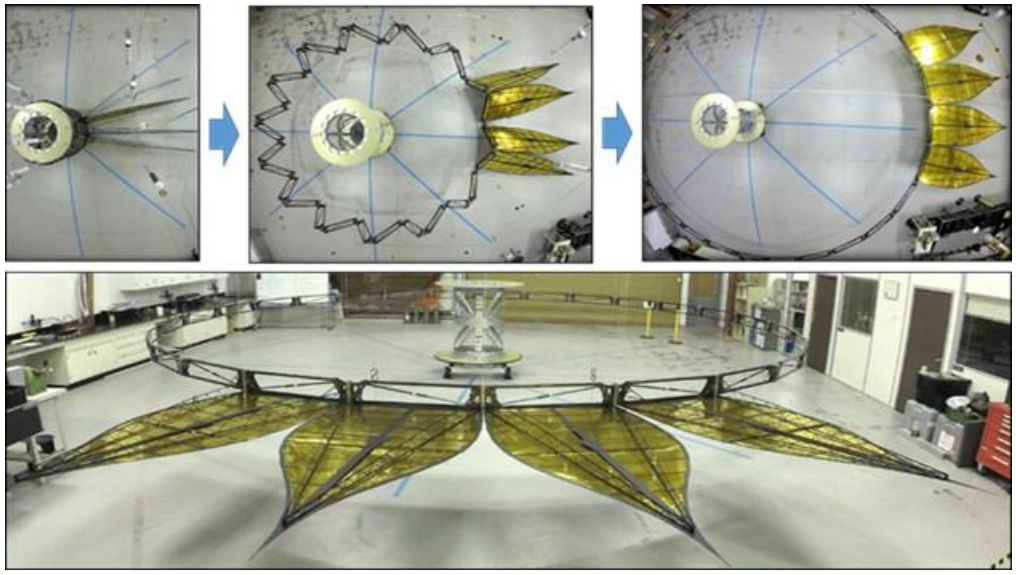

Figure 7. Starshade ½-scale testbed with 10m perimeter truss and 3.5m petals. Testbed proves architecture needed to achieve petal stow and deployed configuration along with re-verification of petal deployment tolerances.

4. CURRENT STATE OF THE MECHANICAL SYSTEM DESIGN

More recent efforts have been focused on the development of a Technology Readiness Level 5 (TRL5) Starshade per the NASA procedural requirements[5]. In summary, these guidelines call for the subsystem or component level validation, in a relevant environment, including a medium fidelity brassboard unit that is built and tested to demonstrate overall performance in that simulated relevant environment. Specifically, the goal of the JPL starshade team has been to address the technology gap list as captured in the Exo-S report[1] and updated on the NASA Exoplanet website[6]. The baseline by which the TRL5 starshade design has progressed has been with regard to the "rendezvous" mission option presented in the Exo-S report[1]. Efforts post-Exo-S have led to the creation of three subsystems with several key constituents to those subsystems:

1) Inner Disk Subsystem
    - Perimeter truss
    - Inner disk optical shield
2) Petal Subsystem
    - Petal structure
    - Petal optical edge
    - Petal optical shield
3) Petal Launch Restraint and Unfurling Subsystem
    - Petal launch restraint system
    - Petal unfurl system

Figure 8 shows the breakdown of the major subsystems that contribute to the petal shape profile. The petal launch restraint and unfurl subsystem does not contribute to petal shape and is therefore not pictured in the deployed configuration shown. The current efforts have been focused on the detailed development of these three subsystems.

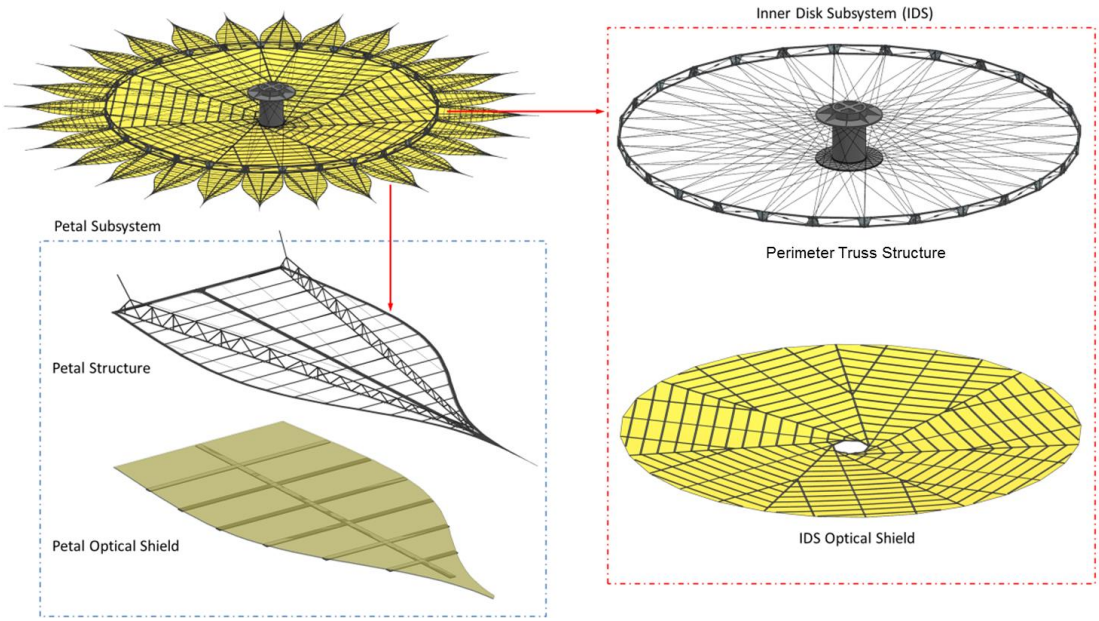

Figure 8. Breakdown of the starshade into petal inner disk subsystems. Not pictured is the petal launch restraint and unfurl subsystem, which does not contribute to the deployed starshade shape profile

<u>Inner Disk Subsystem</u>:

Perimeter Truss

The inner disk perimeter truss component of the subsystem is the most defined. The perimeter truss is the foundation by which the optically prescribed petals are able to perform. As-deployed, the perimeter truss via the tensioned spokes, serves as the positioning element for the deployed petals. Additionally, the truss serves as the frame by which the inner disk optical shield is held in place. For deployment, after petal unfurling, the truss is solely responsible for deploying the petals from the spacecraft out to their final planar position. Additionally, it is responsible for pulling out the inner disk optical shield to its final position. For launch, the truss is the structure to which the petals are restrained.

The testbed, and proof-of-concept, is pictured in Figure 7. This testbed has since been completely rebuilt with medium fidelity hardware and the flight-like interfaces shown in the computer aided design image in Figure 9. Deployment and feature details of this system are described in detail in "Starshade Deployable Inner Disk Subsystem Structure Design and Development[8]."

In order to achieve TRL5 with this prototype, the hardware must be upgraded with flight-like spokes to structurally connect it to the hub. Additionally, all hardware needed to attach and deploy the inner disk optical shield must be added. Once this is completed, the truss will be retested for petal deployment tolerances.

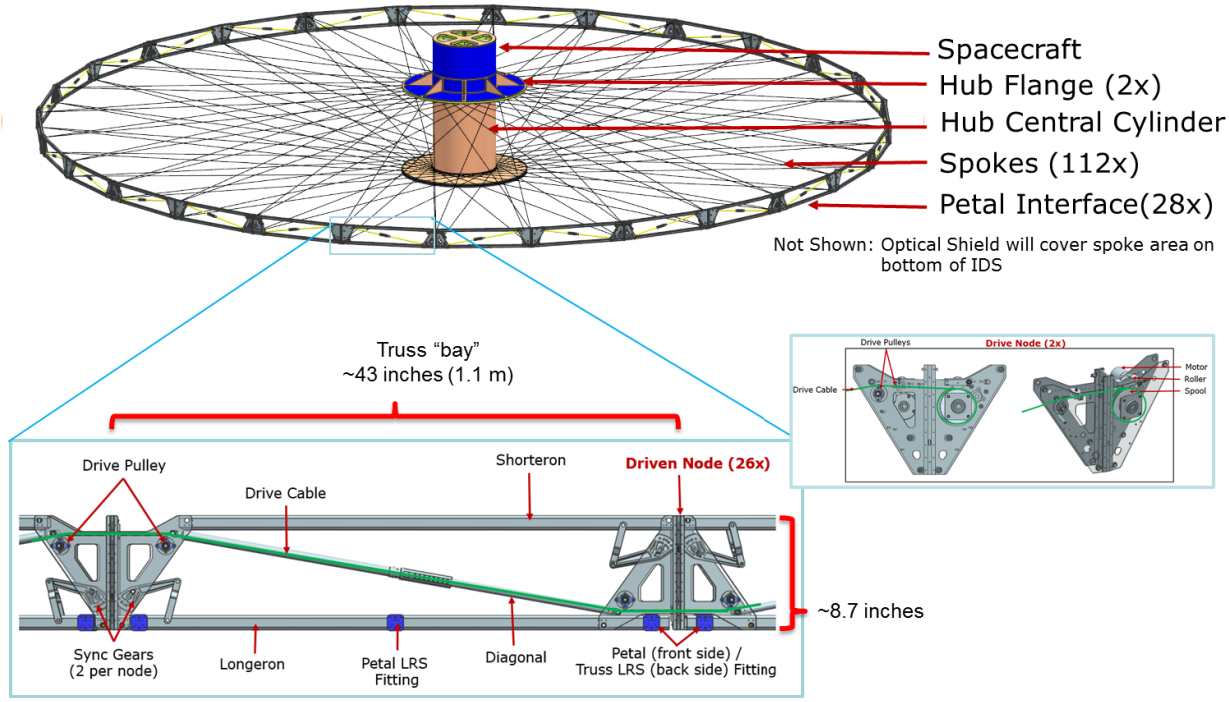

Figure 9. Inner disk subsystem perimeter truss TRL5 design

Inner Disk Optical Shield

The inner disk optical shield is at an early stage in development. There exist three major aspects to the optical shield:

1) The shield material/composition
2) Folding pattern
3) Inner boundary region
4) Outer boundary region

To date, concepts have been developed for all four aspects of the shield. The shield material/composition has the most development because initial efforts were for its application to the petal. A detailed description of its composition and applications can be found in Appendix B of the Exo-S STDT Final Report[1]. The basic shield composition comprises two layers of black kapton with rip-stop lightly bonded and sandwiched to low density foam to create stiff but highly foldable panel. The foam provides a separation between the layers of kapton for micrometeoroid light scatter mitigation. The selection of black kapton is for its inherent opaque properties from a material as thin as 0.001 inches, creating an ultra-low areal density shield. Medium fidelity prototypes using flight-like materials have been produced and tested against launch ascent venting requirements, a key requirement for the assembly. An origami folding scheme has been identified with initial testing on the 1-meter and then 2-meter scale. The architecture as well dynamic modeling of origami applications for starshade application are described in great detail in the Exo-S report[1] and two published papers, "Application of Origami in the Starshade Spacecraft Blanket Design[9]" and "DYNAMIC MODELING AND ANALYSIS OF AN ORIGAMI-INSPIRED OPTICAL SHIELD FOR THE STARSHADE SPACECRAFT[10]". The architecture was expanded to be functionally tested on a more flight-like scaled truss at 5 meters, or ¼ scale, and demonstrated as shown in Figure 10. This 5m scale prototype has been instruments in testing items 3 and 4, the inner and outer boundary region. Several low-fidelity prototypes have been demonstrated on this scale and have greatly informed the requirements for designing a medium fidelity future prototype.

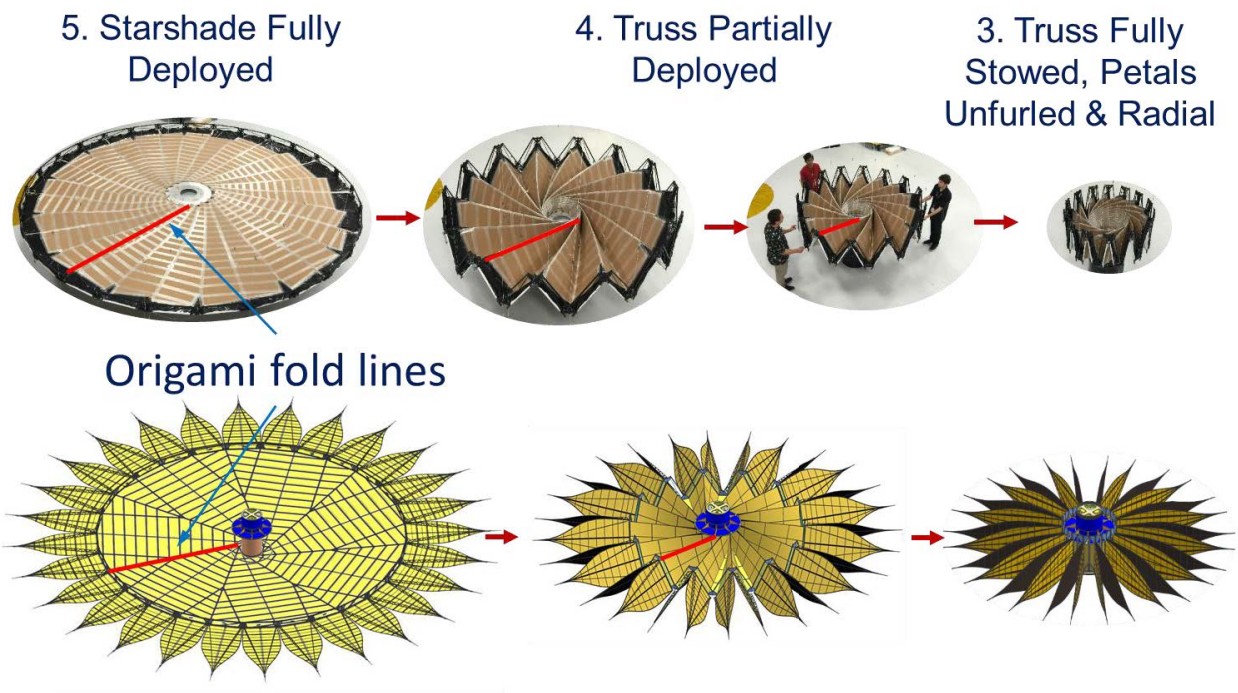

Figure 10. Prototype demonstration of 5m optical shield packaging architecture juxtaposed with computer aided design representation of stow/deploy sequence

The TRL5 inner disk optical shield will culminate in integrating the medium fidelity panel prototypes already developed into the folding scheme along with flight-like material inner and outer boundary region. Additionally added will be all the features to allow the spokes to run along the shield as well as the launch restraint clips that will restrain the shield during launch vibration as well as the deployment clips that will control the shield during deployment as the truss pulls the shield out. After all this is integrated, the inner disk subsystem will be tested against the requirement of accurately deploying the petal roots as was done in the TDEM[8].

<u>Petal Subsystem</u>:

Petal Structure

The petal structure is well developed, drawing from previous work under TDEM efforts. The bulk of the work of the petal structure regards the details of the interfaces to the petal launch restraint and unfurling system and are labelled in Figure 11. Because this hardware does not contribute to the deployed petal position, only the interfaces to accommodate this hardware need be included. Additional features will be the petal base hinges that accurately place the petal with respect to the inner disk perimeter truss as well as the hardware/design of the structure to integrate the optical shield and optical edge detailed below.

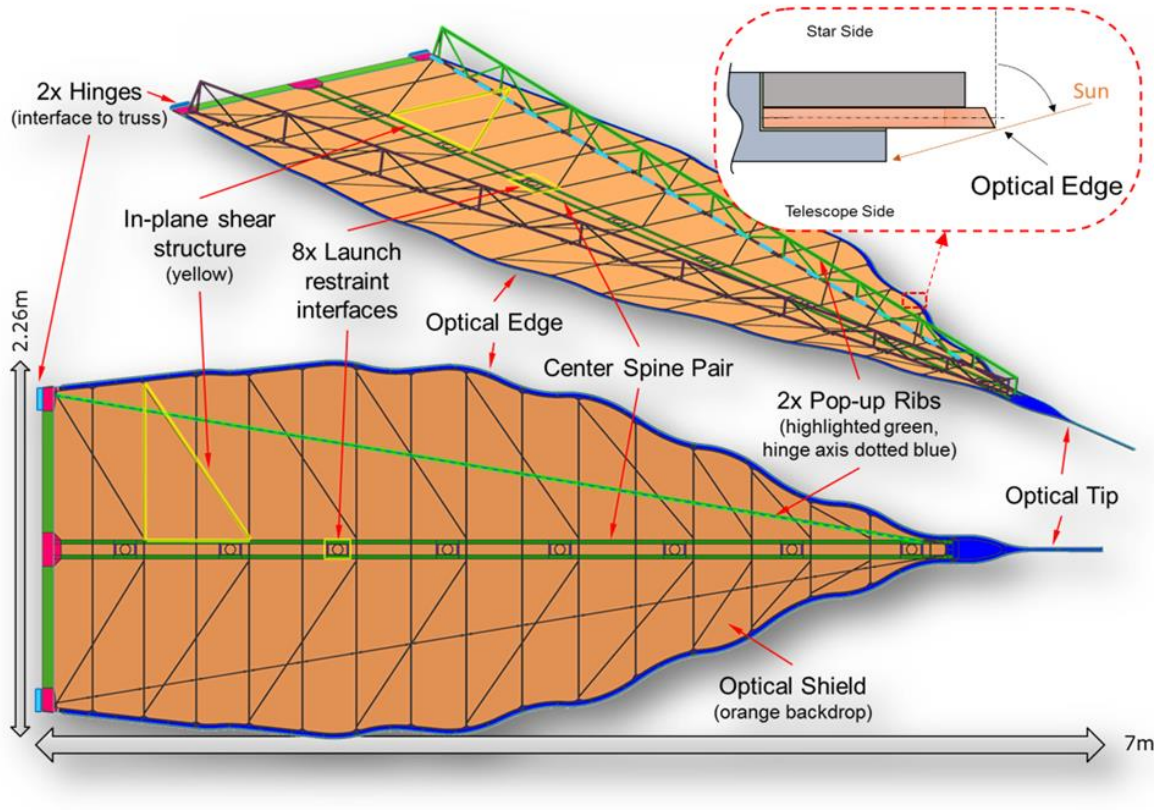

Figure 11. Petal structure with optical edge TRL5 preliminary design

Petal Optical Edge

The petal optical edge must meet the optical profile requirements and reduce scattered light. This requires a 1 micron edge radius to reduce the scattered light such that the starshade is "diffraction limited" for contrast. It should be noted that the 1 micron edge is change to implementation of the requirement as compared to the TDEM, "Advancing Technology for Starlight Suppression via an Eternal Occulter[3]." A cross-sectional view of the optical edge integrated into the petal can be seen in Figure 11 along with the relevant sun angle as sunlight crosses the edge of the starshade. Advancements in the petal optical edge development are discussed separately in SPIE paper ####[####]. In summary, the preliminary requirements for the allowed scattered light have been identified and materials have been selected and tested against the performance requirement. Important to note is that the structure of the petal must be design to seamlessly integrate this optical edge. Once the optical edge is integrated, the petal will be tested against the profile accuracy and scattered light requirements as an assembly. Additionally, the petal will be furled and unfurled to verify accuracy in the simulated stressing environment.

Petal Optical Shield

The petal optical shield has two identified major features, the shield material and the edge boundary region. Currently, the shield material utilizes the same multilayer construction as the inner disk optical shield. Yet to be designed is the edge boundary region that accommodates the differences in coefficient of thermal expansion (CTE) between the required near zero CTE structural edge of the petal and the relatively high CTE of the opaque kapton shield material. This is currently the focus of a NASA Small Business Innovative Research (SBIR). This shield will be integrated into the flight-like TRL5 structure as part of the TRL5 testing. Thermal testing will also be performed against the deployed petal accuracy requirement to verify the optical shield does not distort the petal shape.

<u>Petal Launch Restraint and Unfurling Subsystem:</u>

The petal launch restraint and unfurling subsystem serves to distinct functions. The system must firstly restrain the spirally wrapped stack of petals to the launch restrained truss. Secondly, the system must safely unfurl the petals after

launch without damaging the petal optical edges. To date, the concept for this system is still under development as part of an SBIR. Worth reporting is the launch restraint load path that has been developed. Shown in Figure 12 is a cross-sectional view of the stowed starshade. Important to note is the radial column of petal interfaces labelled "petal launch restraint mechanism" in figure 12. This stack structurally couples the petals together and back to the stowed perimeter truss for launch. The system has been design to structurally bind the spirally wrapped petals along the petal center spines, the workhorse member of the petal. The effect is to create a barrel structure of petals much like the individual boards of a wine barrel are bound together. This structures is then coupled to the strongest and stiffest of the perimeter truss members, the truss longerons, which are restrained to starshade central cylinder. The result, given the configurational constraints, is a structurally efficient load path for the petal back to the spacecraft that does not threaten the precision elements and joints of the truss and petals.

The effort going forward is to produce a functional model that can eventually be integrated with the TRL5 model for testing. It should be noted that as of now, the unfurling system is not considered a technology development and therefore there is no plan to TRL5 test the unfurl subsystem.

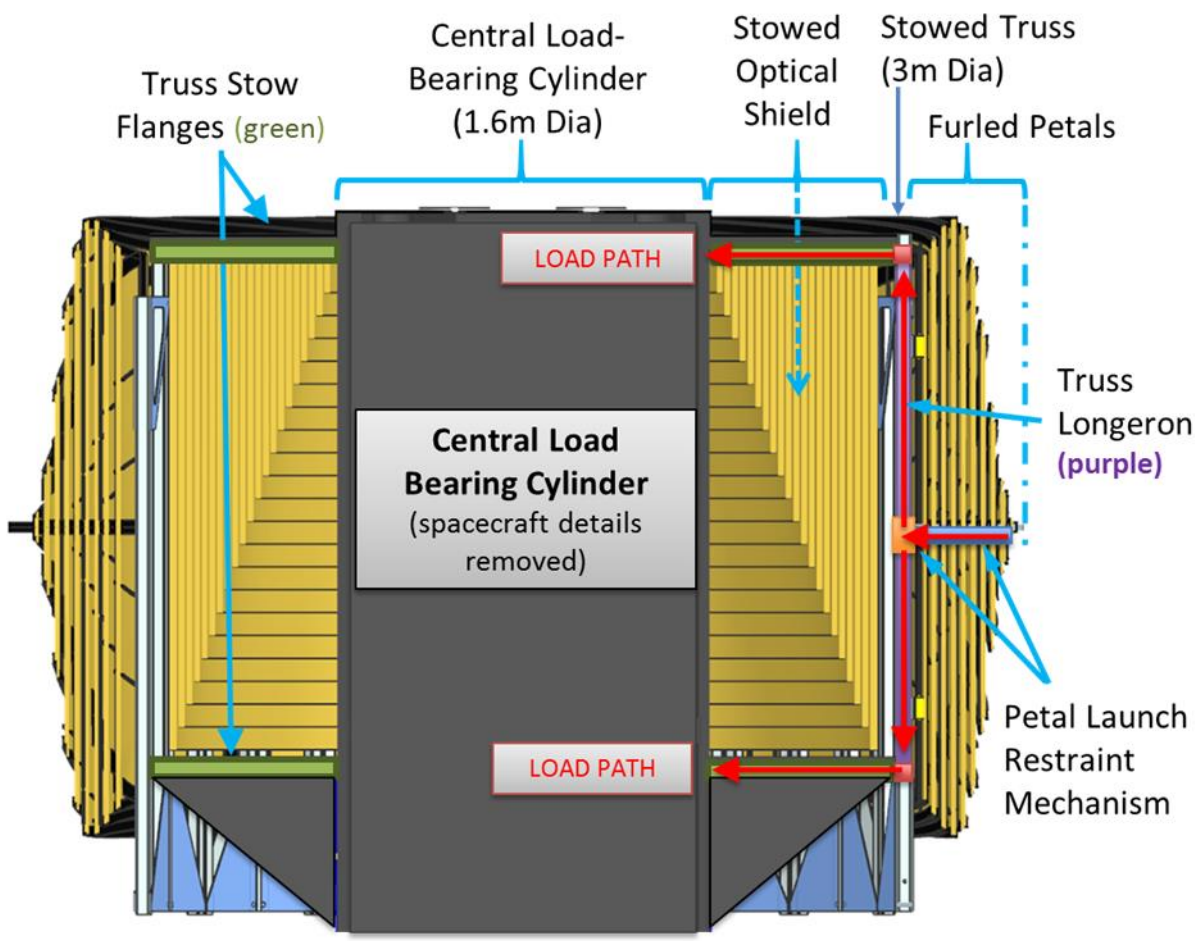

Figure 12. Cross-sectional view of Starshade launch configuration architecture showing restraint hardware requirements and foundation for petal unfurling concept work.

5. FINAL REMARKS

The starshade mechanical technology effort has until lately been a series of individual tasks, mostly NASA Technology Development for Exoplanet Missions (TDEM) awards to develop and verify key capabilities required to enable a starshade mission. These TDEM efforts were instrumental in established the system level architecture for the deployment of a space-based starshade. The demonstrated key requirements included petal profile as-manufactured accuracy as well as the ability to position those petals along the periphery of a ring to the required accuracy. The addition of the NASA funded Science and Technology Definition Team established a mission baseline by which a Technology Readiness Level 5 (TRL5) plan was formulated. Current efforts are focused on formulated a specific TRL5 per the charter plan including required hardware fidelity, environmental testing and performance metrics. The current hardware focus is on adding known and required fidelity to the hardware to enable the TRL5 testing in already that are well developed and fleshing out low fidelity designs and prototypes for hardware that remains at low TRL.

1. ACKNOLEDGMENTS

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A product of the Exo-S NASA Science and Technology Definition Team (STDT) in 201X was a Starshade mission option to rendezvous with the WFIRST at Lagrange point 2.