Research and Development of External Occultor Technology for the Direct Observation of Extrasolar Planetary Systems:

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JPL Starshades Project

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Abstract

Our group conducted work during the Summer of 2012 assembling and developing JPL's Starshades Project under the Technology Development for Exoplanet Missions(TDEM) initiative created by NASA, specifically TDEM stage 2. The goal of the work conducted at JPL by our group was to construct four occultor petals, the main optical components of the Starshade, for the analysis of joint deployment characteristics and of mechanical strain. A Starshade is an optical structure measuring approximately 30 meters in diameter that uses the effects of light diffraction off sheer edges, light scattering, and negative interference between waves to negate all on-axis light in a telescope's image, providing very high contrast that allows planets orbiting a target star to be observed. We completed our engineering goals in the time span of 10 weeks, during which the assembly processes of manufacture, alignment, and structural bonding took place. The Starshade technology and construction process is further discussed in the body of this paper.

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1 Introduction

Our intern group composed of two undergraduate engineering students from Princeton University and myself with another undergraduate from MIT manufactured, assembled, and tested the components of four Starshade Occulter petals in a time span of 10 weeks between June and August of 2012. A Starshade Occulter is a structure designed to cast a shadow into the plane of a telescope's image, supressing the light from a target star, while not affecting the light from any other objects within a certain inner working angle(IWA). In our particular application, a Starshade would allow for the direct observation of reflected planet light from an Earth-like exoplanet, providing a powerful tool for the detection of extra solar planets as well as the capability to analyze the spectra of the light reflected from said planets. To further the development of this technology, our group participated in a TDEM project whose goal was to construct four of the main optical components of the Starshade and test their joint deployment. The construction process was composed of a chain of assembly steps including alignments, bonding, precise position adjustments, and gravity offloading.

2 Assembly and Construction of Starshade Petals

2.1 Material Information and Component Manufacturing

The petal components were machined from three main materials, a carbon-composite extrusion, high density foam, and aluminum sheet. The pieces made from carbon extrusion, battens and longerons, made up the interacting components of the truss structure within the outside edge of the petal. The longerons were cut from long round extrusions while the battens were made by an external contractor with specific slots cut into the square extrusion to allow the longerons to thread through the battens. Interactions between parts are explained fully within the next section. High density foam was used to form the thick center-spine and base-spine of each petal along with aluminum plate cut into face-sheets. All four components, battens; longerons; foam; and face-sheets, were bonded together using a proprietary two part flight-grade epoxy supplied by Hysol Corporation. A thicker aluminum sheet composed two components known as structural-edges as well as the petal tip; all three were waterjetted out of the material, and bonded to form the edge of the petal shape. The final large components of the petals were the ribs which were also manufactured from aluminum, and whose purpose was to provide rigidity to the structure out of plane when deployed. Other smaller components included base and tip doublers, hinges, pop-up tubes with springs, and fastenings/casings for the longerons used to constrain position of both the longerons and the hinges they were threaded through. Specific material properties and component dimensions are proprietary but available upon request given sufficient security clearance.

2.2 Structure

The mechanical structure supporting the optical-edge used for precise starlight supression is shown in Fig 1, with battens, longerons, spines, hinges, ribs, and tip foil shown. Rigidity out of the plane of the petal is maintained by the ribs which are connected to the main longeron through a series of rotating hinges acting as a piano hinge, and to the next longeron out with springs contained within pop-up tubes and ending with a pop-up tube hinge. During deployment, the springs cause the ribs to pop into place from a parallel orientation with the petal face to a perpendicular one, a change that occurs as the petal unfurls from stow position around the central hub. The longerons are threaded through battens placed in a perpendicular orientation with respect to the central-spine, and embedded into the spine itself. The interaction between the spine, battens, and longerons gives the petal structure resistance to shear as well as a spring-like restoring force used during deployment to unfurl the petal. Finally the structural edge shown in Fig 1 is bonded into slots cut in the side of the battens which are cut to specific lengths defining the profile of the petal. The structural edges serve to keep the battens in plane as well as provide rigidity to the structure, they also support the optical edges, not part of this demonstration, which are very precisely placed to follow the designed petal profile.

2.3 Alignment and Assembly Processes

The assembly of the structure required high precision in a few instances for functionality and therefore precise alignment was required. In particular, the most sensitive component to misalignment was the main longeron. Its purpose as the pivot for the rib's piano hinge required the placement of the longeron within the corresponding batten slots to be well known, making the pivot axis straight for smooth deployment. This alignment was performed using a tool known as a jig transit. The jig transit projected our line along the slots, which we measured and adjusted using the optics of the tool. Once a straight line through all slots was identified, we placed stops precisely along the length of the line to reference the longeron position. After the longerons were constrained to their lines through the battens, they were bonded in with the Hysol epoxy.

The other specific alignment that would be required would be the optical edge. In previous work done in the lab, this placement has been done by referencing position from specific guidepoints along the structure using a FARO arm measuring system. The precision that would be employed here is driven by the desire to have a good approximation to the theoretical petal profile.

Noteworthy assembly processes for the project other than alignment and precision location of components include bonding and the prep-work required to bond. Every component to be bonded within a particular bonding session was required to have the bonding surface abraded twice, and cleaned three times with acetone and then alcohol to obtain a clean bonding surface. Areas that would not receive epoxy were taped with teflon tape to prevent spillover of the adhesive. Finally, the two parts of the adhesive were measured out and mixed along with microbeads used to set a bondline between the parts. Once the adhesive was applied, structureal components were aligned in their specific places and then constrained while applying pressure while the epoxy cured for the next 16 hours.

3 Deployment

As mentioned above, the petal structure is meant to stow by curling around a cylindrical hub parallel to the plane of the face of the petal. Once released from this position, the restoring force in the curled spine and longerons would begin deployment, unfurling the petal. At a particular point in deployment, the ribs deploy by being pulled into a perpendicular orientation with the petal face by the springs attached to them and the next outward longeron. Further on in deployment, the truss to which the petals are attached would begin to expand while rotating the petals about their central spines, eventually locking them into an open-face position. Fig 2 shows the shape of the Starshade after the truss has expanded and rotated the petals into place. The figure shows not only the central hub, truss, and petals, but also secondary structural components such as the outriggers which fix the petal in place after deployment.

The purpose of this stowing and deployment mechanism is to maintain the size of the launch package for the scientific mission manageable. Once in space and at the correct position relative to the mission telescope and points of observation, the Starshade would act as a passive structure, never again needing to stow its petals or deploy them again. Therefore, all reliability of deployment testing on Earth serves only to give a measure of confidence as to how well the structure will assume its desired shape in space. As you can only just see in Fig 2, the petals are placed in a back to back and face to face alternating orientation on the truss. As the truss expands, all the petals open to face out, but when stowed the petals curl not only around the central hub, but around each other, decreasing the diameter of the structure enough to fit it all within one rocket fairing for launch.

4 Observing and Research

So far the focus of this paper has been on the Starshade structure as a mechanical design problem and as a passive structure. Here the Starshade Occulter is discussed as a scientific instrument and research tool, and several design parameters are explained. The occulter works by casting a shadow onto the image plane of a space telescope in only a very precise area on-axis between the telescope, occulter, and star.

We can predict the diffraction pattern caused by a plane wave originating at our target star interacting with our occulter due to Babinet's principle. Knowing the output of an aperture of the same shape, we can expect the diffraction pattern for an opaque occulter of that particular shape to have an inverted diffraction pattern of the aperture. If ray tracing and geometric optics explained the interaction between light and our structure fully, we would require only a disk of a particular size at a set distance to cast our shadow, however the plane-wave interaction causes wave front propagation off infinitely many points on the optical edge, scattering of light into our image, and bright spots in the shadow we hoped to create.

To alleviate these problems, we approximate a smoothly apodized and infinitely extending transmissive gradient disk, which would provide perfect shading in our image, through the use of a binary petal system. Each petal has a profile driven by optical requirements to apodize the output function of the light-occulter interaction. As the number of petals in a starshade increases, the approximation improves the "ringing in the curve" is pushed further out from the central bell, and the shadow improves. These considerations for apodization as well as a very precise edge rounded to a particular shape for controlling scattering off the hard-edge, allow the light from a star to be supressed while the light from objects around the star is allowed to enter the image plane and be imaged. One of our petal profiles used in a Starshade occulter is shown in Fig 3.

The purpose of taking such care to design and construct these structures is to allow for the direct observation of exoplanets. The benefits of doing so with an optical system are not only that many exoplanets can be discovered, but that the light reflected off of them can be studied and analyzed, providing spectral information not obtained otherwise. This information is directly tied to properties of the atmosphere of an observed planet, allowing us to study Earth-like exoplanets, and look for the components of their atmospheres that are necessary for life.

5 The Mission and Conclusion

The proposed future development of this technology is a mission involving existing space telescopes or a purpose-built telescope named THEIA(Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy) designed to work with a particular occultor structure. The mission would require the alignment of a telescope with a Starshade at a distance of approximately 50,000 kilometers, a system which is in turn aligned with a star to be observed. Almost any existing telescope could be used however, allowing many occultors to be launched and used for research. Throughout a mission time span of two years, tens to hundreds of exoplanets could be discovered, and the first Earth-like exoplanet that could possibly harbor life could be found.

Before such a mission can be approved and conducted, many technology and concept demonstrations remain to be completed. Our group's contribution to the second technology demonstration of Starshades will be followed by the third demonstration of the technology, which could consist of a full-scale test model developed on Earth. During the past few years, occulters have shown to be a promising technology for exoplanet research and expectations are high for the research that their use could provide. This project provided valuable experience in the design and construction of a JPL style project to our intern group while also allowing us to make a real contribution to science.

6 Acknowledgements

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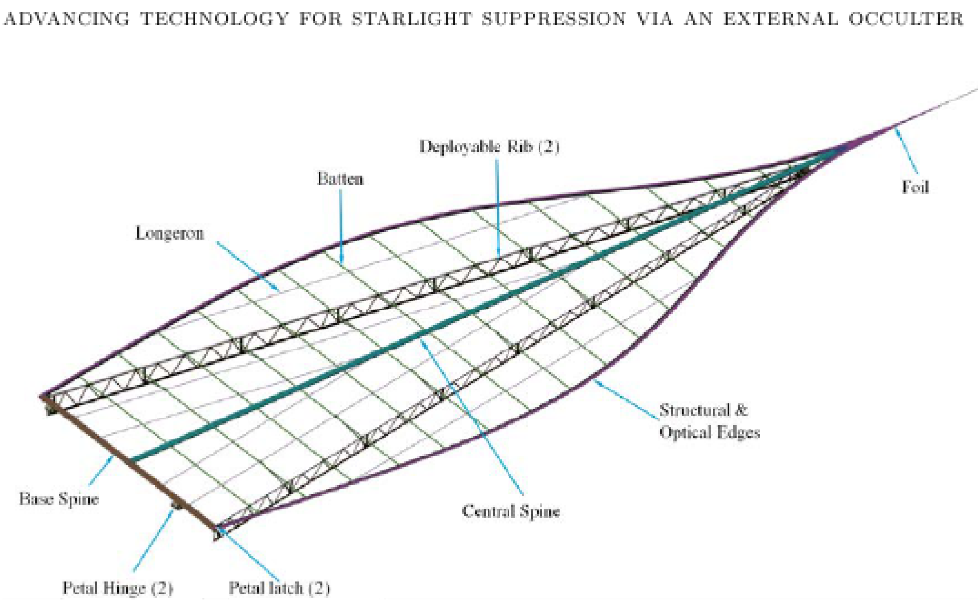

Figure 1: Physical layout of Starshade Petal structure. Diagram sourced from recent Occulter Milestone final report, "Advancing Technology For Starlight Suprression Via External Occulter" , credit to Jet Propulsion Laboratory.

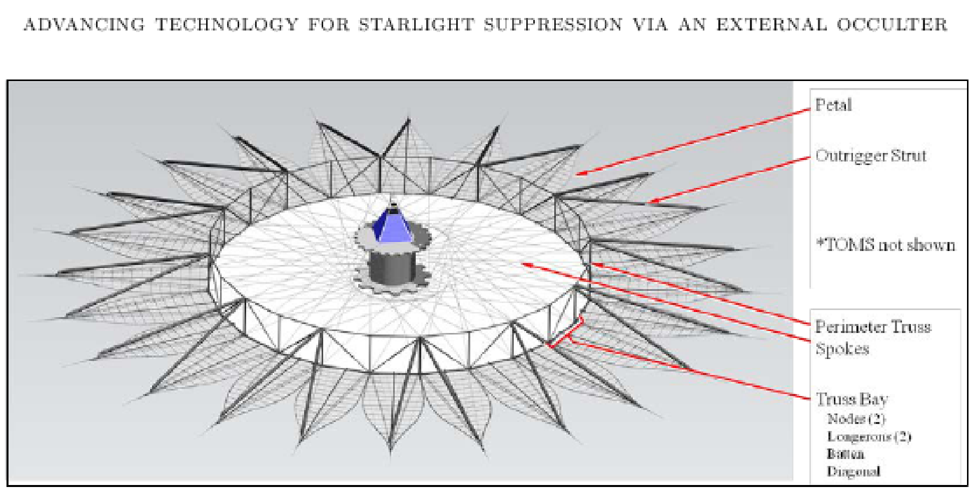

Figure 2: Diagram showing the deployed shape of a Starshade with 24 petals. Diagram sourced from recent Occulter Milestone final report, "Advancing Technology For Starlight Suprression Via External Occulter" , credit to Jet Propulsion Laboratory.

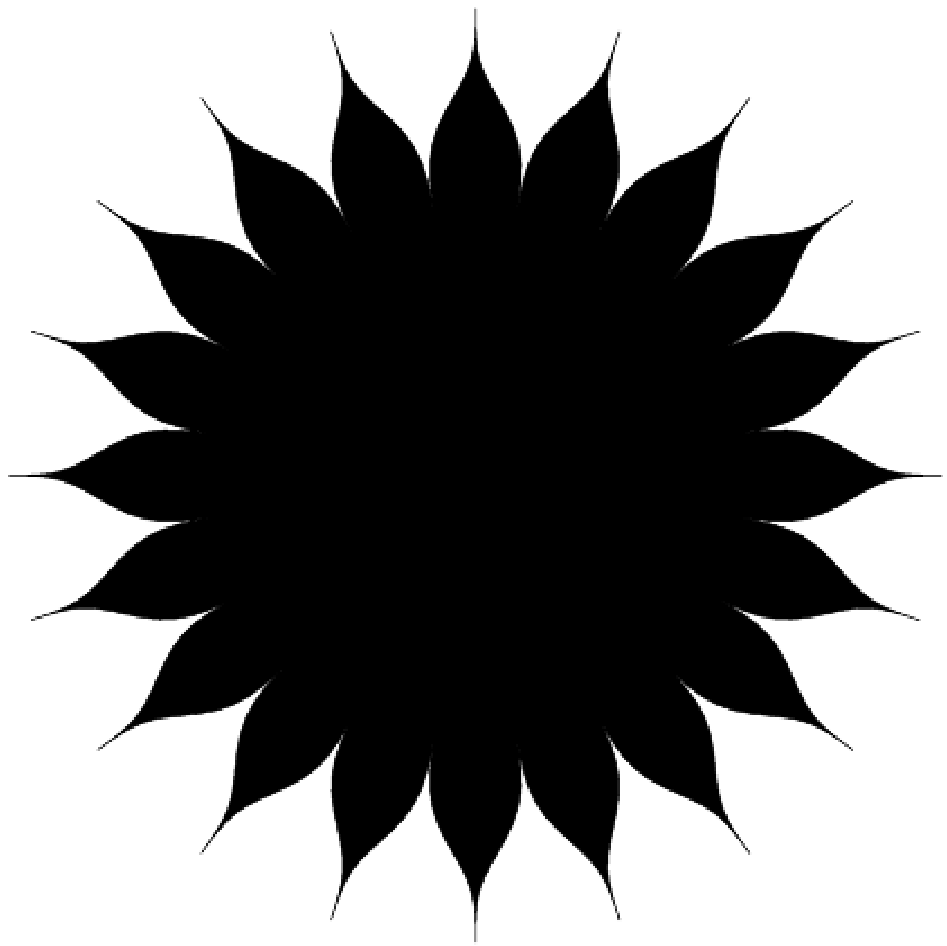

Figure 3: Diagram showing the profile of a 20 petal starshade. Diagram sourced from paper authored by Eric Cady, “Designing asymmetric and branched petals for planet-finding occulters” , credit to Jet Propulsion Laboratory.