Fabrication and Design Testing of 4 Petals for Deployable Starshade Prototype

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Final Report

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Abstract: One of the next steps in the exoplanet search is the development of occulter technology. Starlight suppression for a telescope would provide the ability to more accurately find and characterize potential true-Earth analogs. Coronagraphs have been the subject of much research in recent years but have yet to prove themselves a feasible approach. Attention has now turned to external occulters or starshades. A large occulting mask in front of a telescope should provide a comparable optical resolution to a coronagraph. Under a TDEM grant, a proposed starshade design was demonstrated to exceed coronagraph resolution by at least an order of magnitude. The current project is to demonstrate that the current design can be manufactured and then properly deployed. 4 sample starshade petals were constructed, ready to be attached to a pre-existing deployment truss. Time was spent detailing and modifying the petal construction process, so that future petals could be constructed at a more accurate and faster pace.

Background

The proposed research area is the creation of THEIA, Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy and its companion occulter. The THEIA observatory is an on-axis three-mirror anastigmat telescope, with a Star Formation Camera (SFC), a dual-channel wide field UV/optical imager; UltraViolet Spectrograph, a multi-purpose spectrometer; and the eXtrasolar Planet Characterizer (XPC), which consists of three narrow-field cameras and two R/70 integral field spectrographs.[1]

The telescope is accompanied by an occulter for starlight suppression. The occulting mask is 40 m in diameter, comprised of two main sections: a deployment truss and attached 3.7 meter wide petals. Figure 1 illustrates the petal structure that will be constructed.

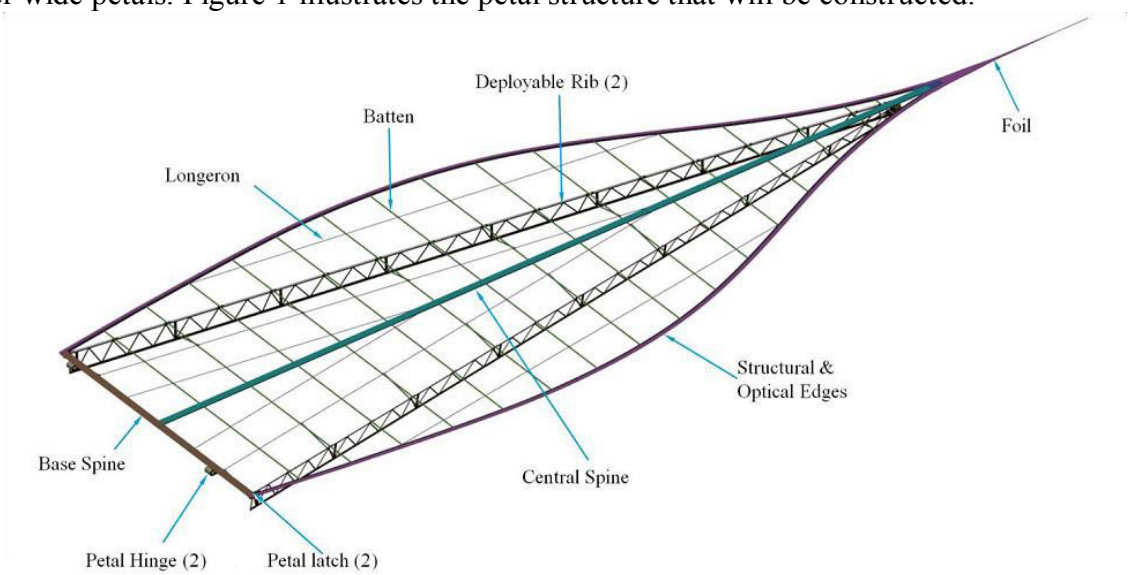

Figure 1: Petal structural details[2]

The petal shaped edge is designed for maximum light suppression, using a graphite epoxy sheet (the optical edge) attached to the structural skeleton (also utilizing graphite composite material). The battens and longerons provide in-plane stability, as the apparatus is very flexible. The flexibility of the structural skeleton allows for wrapping around the collapsed deployment truss. The apparatus is designed to fold in on itself to fit inside a 5 meter launch fairing. Once released, the various petals will unfold until the ribs deploy, which provide strong out-of-plane stability. Figure 2 illustrates such a deployment.

Figure 2: Petal Deployment Phase 1[3]

For proper starlight suppression, the occulter must be deployed with millimeter accuracy.

[1] Kasdin, THEIA.
[2] Thomson.
[3] Ibid.

A thermo-optical micrometeoroid shield (TOMS) will be attached to the occulter provide adequate protection from micrometeoroid damage and resulting optical contamination.

One of the primary goals of the THEIA mission is to find and characterize true Earth analogs: an Earth-size planet in an Earth-like orbit about a Sun-like star. Use of the XPC will enable detection and identification of spectral features, in particular biosignatures. The absorption features of water and methane, for example, are in the XPC spectral range. The XPC should also be able to detect photometric variability, which could lead to measurements of a planet's rotation rate, detection of weather, perhaps even the inference of continents. The starlight suppression system will allow THEIA to make the most detailed observations of protoplanetary and debris disks than ever before. This will help better understand the formation of planets. The suppression system also enables improved star formation observation, which will lead to more information about how stars form galaxies in different environments.[4]

Objectives

Two years ago, the project group first completed a POC (proof of concept) model of a single petal, as part of the TDEM 1 effort. This petal was used to demonstrate petal structure and possible deployment methods. In the last couple of months, the group constructed a full-scale petal model, adhering to strict material and optical tolerances. Optical tests on the model demonstrated that the petal could achieve the contrast requirements of at least 10^{-10}. The precision test also raised issues in petal construction, which will be addressed in future phases.

The next phase of the TDEM effort is to demonstrate proper deployment of the central truss and petals to a necessary accuracy. A team of four interns will be constructing four of these occulter petals using similar materials but relaxed optical tolerances. These petals have been designed for a 21 m starshade and contain an optimized structural edge for the smaller size. In accordance with the relaxed tolerances, only the battens and longerons will be constructed of pultruded graphite fiber rods. The additional components will be constructed from anodized aluminum. These petals will be attached to a pre-existing deployment truss to demonstrate petal functionality, including stiffening rib deployment and stowing wrap around the hub. A successful deployment of these petals will indicate a usable deployment approach and correct petal construction.

Approach:

The petals were to be constructed using two optical tables and assorted optical tools to determine proper alignment of the petal pieces. The team of four interns was to be divided into two groups, each working on the construction of a petal. One team would be lagged behind the other, so that issues in petal construction would be addressed and resolved, thus expediting the process. Once two petals have been constructed, the team would begin work on the remaining two petals, hopefully having addressed any issues that arose in the first construction phase.

The first days in the lab were used to familiarize ourselves with the equipment that would be used in petal construction. I had never used an optical table before, and so I learned how it functioned and the types of optical tools, for example optical cylinders to set straight lines or optical clamps to fasten down an object. The previous phase of the TDEM effort, a full scale petal with functioning optical edge, was removed from the table and hung on the wall, both freeing up space and giving the lab a visual reminder of the final product. It also served as an introduction to the petal components.

[4] Kasdin, TDEM.

The various components were then checked to verify that they had been correctly produced, and it was discovered that there were several errors in component production. The anodizing vendor had anodized the wrong locations on the tip doublers and the structural edge. As it is not recommended to bond to anodized aluminum (bond strength is reduced), the parts had to be marked where the anodizing should be removed and were then returned to the vendor for correction. The fit-check also revealed how flexible the structural edge could be. Despite being fixed at either end, the edge could fluctuate over 1/16 of an inch. This alerted us to potential alignment issues with the edge, and we added further constraints in the alignment process to verify correct positioning.

After becoming comfortable with the optical tools, the team began to lay out the position of the petal on the optical table. We started by establishing a straight line down the length of the table for the center spine, positioned so as to ensure the petal would fit on the surface. Once the center spine position was established, the base spine was placed in perpendicular alignment. Using measurements of the base spine and center spine, the structural edge was set in place with optical cylinders, and the position of the edge, base and center spine then marked on the table with permanent marker.

We spent a day learning the details of bonding: how to prepare an object to be bonded and how to properly use adhesive. After the lecture, we proceeded to bond key fastener components to the base and center spine, leaving them to cure overnight. At this point, we also continued construction on the lagging petal. Next, the position of the battens was fixed on the table using optical clamps and straight-edge/ruler. Their lateral alignment was established by drawing a taut string from first to last batten hole, thus establishing the longeron line. The position of all the longerons was marked on both tables to facilitate the placement of optical hardware.

However, we discovered that the placement of the base spine for both petals was incorrect by 1/10 of an inch. This was fixed in one petal by simply adjusting the position of the base spine, but in the other petal, the position of the battens was also determined to be incorrect. The batten placement and base spine for the lagging petal had to be completely redone. While the batten placing was being corrected, the support foam for the center spine was cut. We also continued preparations of the battens for bonding. It was during this process that we decided our method of batten placing was inaccurate due to the way the battens had been cut: the ends were rounded and did not provide a clean alignment edge. The edges were subsequently cut and the positioning re-aligned. The structural foam was then bonded to the center spine face sheet, and work continued on the second petal.

Figure 3: Batten placing established and foam cut

At the end of the third week, we bonded the structural foam and battens to the center spine for the second petal. When we returned to work the next week, we rotated the petal skeletons, using a straight edge to compensate for the lack of rigidity. Once the petals had been flipped, we removed as much surplus epoxy as possible, to give a cleaner edge for more accurate placement. It was also important to clean off the epoxy, as a cleaner edge has better presentation.

Work then began on placing the structural edge. It had been decided that the structural edge should be bonded to the petal 1 ¼ inches off the ground to facilitate proper positioning and cleaning after the bonding process. In order to bond the petal off the table, we had to also raise the straight line for petal placement, ensuring the petal remained straight and immobile for correct edge placement. Though at first it sounded easy, complications soon arose with how exactly the petal could be secured at that height. The optical cylinders we had been using to establish position were unfortunately a different diameter at the base and thus could not be used to elevate the line. After several design iterations, we settled on using 6 very large optical cylinders that had consistent diameters to establish the base straight line. Once this line was established, a straight edge was elevated and used to position smaller cylinders as constraints.

It was at this point that we began to have issues with the straight edge we were using. A long piece of bosch had been bonded to a 12 ft. ruler to give it straightness and prevent deflection. It had given straight lines for previous work, but when used to align multiple cylinders to the elevated line, it was inaccurate. The metal was flexible enough that minute deflections were induced between the cylinders, creating an S-curve instead of a line. Luckily, the lab had an industrial straight edge: a piece of metal that had been manufactured explicitly to give a straight inflexible line. Using this new edge, all the cylinders were placed correctly, and the petal was then elevated into position using pieces of bosch underneath the battens. .078 inch washers were added to special pieces of bosch, so that the structural edge would sit comfortably in the batten slots.

The structural edges then had to be prepared for bonding. This was a far more time-consuming process than previously anticipated. The edges had to be precisely taped to avoid epoxy overflow, and when we found that we could not bond on that particular day, the cleaning-abrading process had to be repeated the next morning. We were also careful to tape surfaces near the bonding sites to prevent epoxy spill-over, such as the top of the tip doubler. Once all the preparation steps had been completed, the structural edge was bonded in using Hysol flight-grade epoxy. On either side of the bonding sites, 1 lb scuba weights provided bonding pressure. We also noted that in the second petal, the battens should be better secured to prevent shifting during bonding.

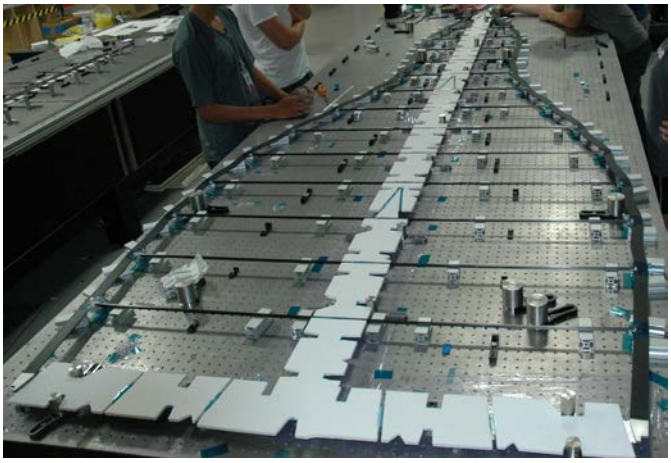

Figure 4: Structural edge raised and positioned

The petal was then lowered back to the table and clamped down. The next phase of the project was to learn how to use the jig transit. The jig transit is a telescope-like device that allows the user to sight an extremely accurate straight line. The goal was to use the jig transit to establish a straight line for the two rib hinge longerons. It was important that these be straight to prevent binding on the rib hinge, which would impede deployment. The learning curve on the transit was steep: it took us nearly two full days to sight one line. As one team worked on the jig transit, another began preparing the longerons to be bonded in: sanding the correct spots and making sure they were properly cut. We also continued work on the other petal. After both rib hinge longerons were transited, the table and petal were prepared for bonding. The Teflon plastic on the table had to be patched, and the petal/longerons needed to be shimmed to the correct height. Foam plugs also had to be cut to position the longerons correctly inside the center

spine. It was frustrating at times, because we were forced to delay bonding for forgetting simple steps in the preparation process. At last however, the longerons were bonded in. While the epoxy was still fresh, a second round of tip doublers and corner fillers were bonded, using a new positioning scheme to ensure correct bonding position. However, we discovered that we had missed one of the pop-up tube attachments and had bonded the longeron in without it. Though not a crucial mistake, it was a wake-up call that we needed to be very diligent to make sure all the necessary components were in place before bonding. Before the day was out, we prepped and bonded the second center and base spine to the first petal.

When we returned from the weekend, we began to prepare the ribs for attachment. Like the structural edges, this was also a process that took much longer than expected. Not only did the surfaces need to be carefully taped, the anodizing needed to be removed in certain spots to provide sufficient surface area for bonding. The rib edge itself also had a number of irregularities that had to be sanded down. The ribs also needed to be bonded in vertically, so we set up a system that allowed for vertical stability: the heavy weight blocks were used along the length of the rib for support. Once block spacing details were worked out, the rib and base spine doubler were bonded.

While the bond was curing on the first petal, we began to do the jig transit for the second petal. Given our prior experience, this process went much faster: both longeron lines were established in roughly a day. Preparations continued for bonding in the longerons as well as the center/base spine for the second petal, as the foam was cut away on the first petal. The result is shown in Figure 1.

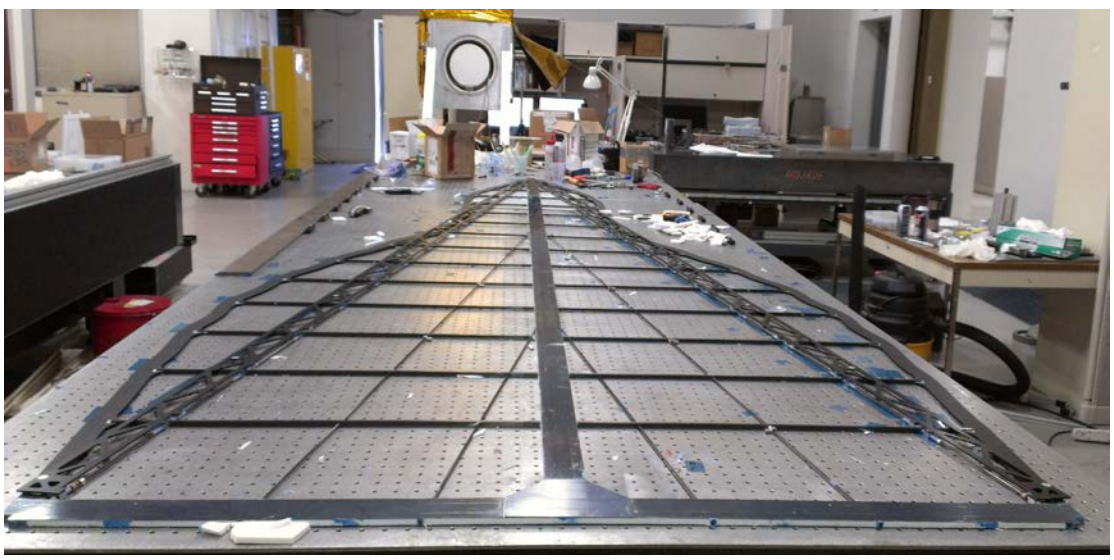

Figure 5: First petal nearly completed

After a day of preparations, the longerons and base/center spine were bonded in. Before the petal was removed from the table, we were divided into two teams, one for each petal. We each created a schedule for petal assembly to ensure that we would finish all the petals by the program end date. It was determined that one team would be lagged behind the other to allow for the completion of the second petal. Once the schedules were completed, the first petal was then removed from the table, and one team began work on the third petal. As the other team worked on the third petal, my team continued progress on the second. The ribs and rib hinges were prepared for bonding, using the dremel for the first time to remove incorrect anodizing

along the hinge and edge. We also decided that it would speed up the schedule to bond the remaining tip doublers and corner fillers while we bonded the rib hinges. This second round of doublers/fillers bonding came with increased clamp placement and attention to alignment, all of which took much more time than anticipated. Preparations finally complete, the rib hinge and other components were bonded in.

When the epoxy had cured, the rib hinges were tested and displayed excellent mobility. We cut the excess foam off the petal and moved it off the table. We then began to lay out the alignment for the fourth petal. We had taken care in our cleaning to keep many of the markers from the second petal, so the layout process was accelerated. By the end of the day, we were completely on schedule. The next couple of days proceeded without a hitch. We were completely on schedule with our assembly process, and in fact, gaining time on the other team. We had made several process improvements to speed things up: for example, we used large constant diameter cylinders when first establishing the base and center spine line. This allowed for easy elevation when bonding the structural edge. We were much faster in our assembly as we fully understood the methods of petal construction, and the presence of our own daily schedule helped move us along as well.

We were preparing to bond in the longerons, when we discovered that not enough rib hinges had been ordered. The project plan had originally called for the construction of three, not four petals, and so there were only rib hinges for 3.5 petals. Construction was completely halted. Until more rib hinges could be procured, no major advancements could be made on the fourth petal. However, the time was used to prepare the lab for the arrival of Professor Jeremy Kasdin (P.I) and the NASA Director for Astrophysics, Dr. Paul Hertz. The lab was completely cleaned, and the POC petal was prepped and deployed for their tour.

With construction halted on the fourth petal, we attended to other small details that needed to be finished. The petals were going to be hung on a sample wooden deployment hub in the lab, and a deployment mechanism for the ribs needed to be installed. I was put in charge of assembling pop-up tubes for the rib deployment, while other team members worked on attaching the petals to the hub. From the construction on the POC, we had an established assembly method for attaching the tubes, though I made some adjustments. However, since the current petal size was smaller, testing needed to be done to determine what type of spring would work best to deploy the rib. Using existing data on spring deflection and deployed loads, I selected 3 types of springs that I thought could work. I then performed deployment tests with one of the springs to better understand how the rib would deploy and what load was really needed. That deployment test gave a benchmark for how much force was sufficient to deploy the rib. After consultation, I chose a weaker spring and installed this spring for all the pop-up tubes in a full petal. This petal was then hung on the hub and shown to deploy correctly.

By this point, the replacement hinges arrived, and work continued on the fourth petal. Two team members continued work on this petal while I installed the pop-up tube assembly on all completed petals. We had also discovered that several pop-up supports on the longerons had not been installed. Another team member was tasked with designing a replacement support that could be inserted on a point by point basis.

Once the ribs were bonded onto the fourth petal, the team hung a second petal and then deployed both petals simultaneously. In the final week, work will continue on designing a miniature occulter (max diameter 3 ft) so as to easily demonstrate starshade functionality. One team member will be designing the expansion truss, and I am working on the petal design. All four petals were prepared for full functionality and should be hung by the end of the week.

Figure 6: Two fully functioning petals

Results and Discussion

The TDEM2 effort revealed more insights into petal construction and how future petals could be more accurately and quickly manufactured. One of the first insights came regarding the petal construction schedule. It became apparent later on in the project that we had fallen behind schedule, as the petal construction learning curve was steeper than anticipated. Though many of the assembly steps seemed simple in principle, they often took much longer because we needed to develop new and more efficient methods to accomplish those tasks. Furthermore, not having previously completed a petal, we were often not sure what steps needed to be taken, which resulted in a fair amount of downtime. However, when the first two petals were complete, the four interns were divided into two groups and tasked with creating our own schedule to assemble one petal. My team, feeling the time pressure to finish before the program end, outlined a fairly ambitious petal assembly schedule: we planned to finish the petal in nine days rather than the five weeks it had taken prior. We made sure to detail all the small steps needed for crucial bonding operations, which had proven to take the most time and effort. We discovered that we had a fairly accurate conception of how long processes would take us from completing two prior petals. Though we begun construction on the fourth petal lagged two days behind the other team to free up lab resources, by the time construction had to be halted, we were only a day behind. We had collapsed a five week assembly schedule into a near-complete construction in nine days. Setting our own schedule drastically improved the pace of lab work, and it was a very good experience to conceptualize how a project schedule might progress.

We also gained experience with the use of flight-grade epoxy and the procedures that accompany it. Surfaces that were to be bonded had to be prepared in a specific manner. Also, as pressure was needed to complete the bond, components could shift during the process. We had to establish creative ways to correctly establish component position during bonding as well as providing weight. For the first petal, often we aligned components based on sight. For example, we discovered after bonding the tip doubler to the center spine that the two had shifted during the process, though they had initially appeared aligned. In the interest of correct fit, we redid the process with two new pieces, using a combination of optical cylinders and clamps to provide a fixed alignment for the pieces. The bonding schedule was also responsible for many of our original delays. Ideally, bonding would be completed at the end of the day and left to cure overnight, so that the pieces could be used in the morning. However, during the first two petal assemblies, bonding occurred at non-optimal times, for example in the mid-morning, which would leave the petal unusable for the rest of the day. Additionally, components to be bonded needed to be abraded and cleaned the day of bonding, a process that could take up to an hour. If

bonding was not to occur that day, the process would have to be repeated, which put us further behind schedule. However, for the last two petal schedules, bonding occurred at optimal times, drastically speeding up the assembly process.

Another important area of consideration was the use of precise metrology for petal assembly. We strove to be as accurate as possible, often down to a thousandth of an inch. We learned how to use the jig transit, a device for establishing a truly straight line. The jig transit also allowed us to examine the straight edges we had been using, which revealed that they were not really straight. Our first straight edge: a long ruler secured using bosch was moderately straight on one side but subject to unacceptable deflection when used along long stretches. Even the professionally manufactured straight edge deviated in some spots as much as .005 inches. For the purpose of establishing lines for the center and base spine, this deviation was not crucial, but the straight edge could not be used at all to set the rib hinge longerons. Instead, we relied solely on the jig transit for the crucial longeron alignments, as accuracy here was very important for correct rib functionality. However, the inaccuracy of the first straight edge did not pose too much of a problem for the first petal, as it deployed properly.

We also realized how important it was to check measurements before placing components on the table. A large amount of time was lost in re-doing the placement of the battens for both petals, an error which could have been fixed to some degree if we had fully checked the component schematics. It also gave us an appreciation for how seemingly negligible placement errors could dramatically affect later processes. The lack of a clean initial edge on the batten did not originally present a problem but later induced errors in longeron slot alignment and structural edge fit. It was a good reminder that precise measurements are good only as long as the components themselves conform to that same precision.

In addition, I feel I better understand the importance of good presentation. It was emphasized to us that the petals should both function well and look as though they should function well. We are a very visual culture, and a visual assessment of an object can be just as important as a demonstration of its functionality. We were very careful to clean the petal of excess epoxy and to color un-anodized aluminum and foam with black marker to improve the petal's appearance. When completely finished in this manner, the petal looks sleek and professional. A sloppy appearance could hint to sloppy construction methods. As the project is still in development stages, we want outside visitors to see our petals and be convinced in the viability of the project. We also began work on a small scale model of a full starshade. The model will be 3ft across, so as to fit comfortably on the conference room table. The goal is to construct a fully functioning truss with petals attached to easily demonstrate starshade functionality. Having a functioning physical model provides a more visceral sense to what a starshade really is.

Further research will be conducted on the springs used for rib deployment. In the first spring test, the spring load would not allow the rib to stow when laid on a surface. In later tests with a smaller load, the rib would stow flat. The characterization of what is desirable in rib behavior must be better defined. The spring load from the second spring may not be sufficient to deploy the rib in all circumstances, but in current test cases, it has successfully deployed two petals and does not produce excessive force. The first spring produced potentially excessive force but would almost certainly deploy the petal in all circumstances. The first spring will be used as the deployment mechanism for the fourth petal to test full-scale deployment. Deployment methods for a large number of petals must also be considered. The petals must be released at the same time and deploy at the same speed and orientation with respect to one

another. The last week of the project will be spent analyzing deployment behavior and attempting to address this question.

Conclusions

This part of the TDEM2 effort demonstrated that four petals could be manufactured in under ten weeks, leaving time for deployment testing and ancillary tasks. The team also documented the construction process and made adjustments to allow for increased speed and accuracy. A sample hub in the high bay allowed the team to deploy the petals and begin to develop deployment methods for a large number of petals.

It was very rewarding to see the entire project come to fruition, from the first schematic read-through to final deployment tests. We were able to use the petals to demonstrate the physical characteristics that we were hoping they would exhibit. For example, it was fascinating to test the plane flexibility of the petal: without the ribs, the petal was very flexible, but when the ribs deployed, the petal became very rigid. This was a crucial design characteristic for the petal, as it must be flexible enough to wrap around the hub but deploy rigid for occulting functionality. Deployment tests on the full-scale truss will further test design characteristics, such as deployment accuracy.

Acknowledgments

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