Starshade Technology Development

Astro2010 Technology Development White Paper

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ABSTRACT

Since the development of a design for a high-performance, technically feasible, external occulter, known as a Starshade (Cash 2006), a variety of missions have proposed pairing a starshade with a space telescope to enable high-contrast imaging. The most notable of these is the New Worlds Observer mission concept, which uses a starshade with a diffraction-limited telescope to perform terrestrial planet finding. Beyond terrestrial planet finding, starshades have been proposed to accomplish many science goals including planet formation, AGN composition, and exo-zodiacal light characterization. In the course of several ASMC studies, the NWO team and others have been studying the incorporation of starshades into a wide range of mission concepts such as ACCESS, ATLAST, and JWST. While the NWO team has largely used existing technology in the design of these starshades, we have identified several areas of technology development that will enable us to rapidly demonstrate and implement starshades for the missions under study. While most of the core starshade technologies are mature and can be adapted to this purpose in months (instead of years), integrating the pieces of these technologies into a coherent whole needs development and demonstration funding. With immediate funding, the starshade is a technology that maybe used in the 2010's.

NASA has invested considerable funding into technologies for PlanetQuest and Terrestrial Planet Finder, with the eventual goal of identifying and studying Earth-like planets. The choices of technology were made about a decade ago, but the starshade concept was invented only four years ago. There have been no open opportunities to compete for technology funding for exoplanet missions during that period, and consequently all the study funding has continued to flow to the older concepts. We feel that starshades have the potential to greatly reduce the cost, speed up the launch, and improve the scientific return of terrestrial planet finding programs and are therefore a prime candidate for technology funding. We discuss in this whitepaper an immediate, affordable approach to making starshade technology suitable for a 2010 to 2020-era implementation.

I. Introduction to Starshades

An external occulter, or starshade, works as shown schematically in Figure 1. An opaque screen flies in the line of sight from the telescope to the target, in this case a star. The idea of a starshade is not new (Spitzer 1962), but the problem of light diffracting around an external occulter made the designs impractical for revealing Earth-like planets (Marchal 1985; Copi 2000). Four years ago, Cash (2006) developed an apodization function that, for the first time, offered an effective, affordable, and technically feasible external occulter.

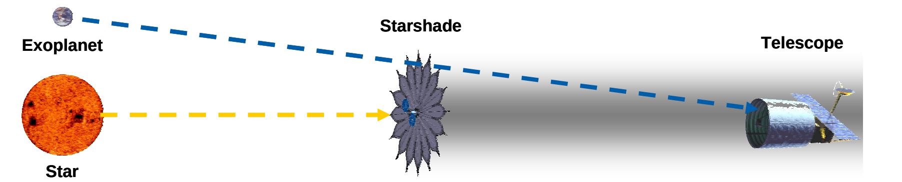


Figure 1: NWO's cost-effective starshade shadows the telescope from the star, while light from a terrestrial exoplanet passes the edge of the starshade unimpeded.

The offset hyper-Gaussian apodization function reduces diffraction into the shadow by many orders of magnitude; Figure 2 shows the parameters of this apodization function. If the shade is sufficiently distant, it will subtend a small angle to enable imaging terrestrial exoplanets. A starshade with 2(a+b) = 50 m (the effective diameter), operating ~80,000 km from a 4 m telescope is capable of suppressing the starlight by 10^{10} within 50 mas, the inner working angle (IWA) of the system. The New Worlds Observer (Cash 2007) project was the first to use such a starshade.

The starshade technology cleanly resolves many issues of high-contrast imaging: by enabling full suppression of the starlight before it enters the telescope, it relieves the telescope of all special requirements such as ultra-high quality wave front correction. Indeed, the NWO project has shown the feasibility of using starshades with any telescope flying in a low-acceleration environment like the Sun-Earth L2 point (Lo 2008). Starshades are ready to build immediately – we outline a plan towards TRL 6 in 3 years. This plan is focused on the technologies needed for starshades up to ~50m, with TPF-class science. This roadmap also provides a solid grounding for developing the next generation of starshades, capable of working with very large (<10 m) telescopes.

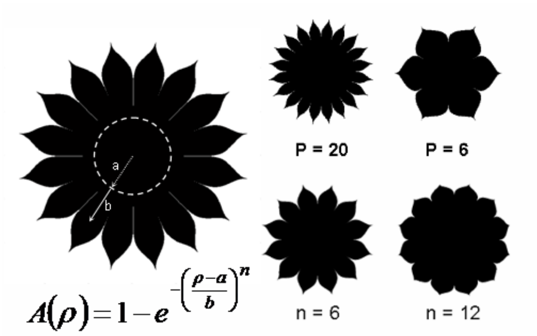


Figure 2: The apodization function, A(ρ), describes the shape of the starshade and can be optimized for suppression level, wavelength range, shadow size, and IWA.

II. Starshade Science

Starshades allow for direct observation of high-contrast targets with very small angular separations. They have primarily been developed for use in finding and characterizing terrestrial exoplanets, though this is certainly not their only application.

Observing Earth-like planets around other stars required that the starlight be suppressed by a factor of ~10^{10} and that the light from the exoplanet, which is only ~100 mas away, have as high a transmission as possible. In addition, any information that can be preserved about the conditions in the rest of the extra-solar system will help in interpreting the observations of the exoplanet. For example, the distribution of extended light from dust in the stellar system is a sensitive tracer of the system's orbital dynamics. Planetary orbital resonances will be displayed as gaps and enhancements in the dust. Tiny planets, even those too small to be seen directly, will leave distinct marks. The dust seen gives us critical information like the inclination and orientation of the system's ecliptic plane (Figure 3). By eye, one can place an ellipse over the system, estimating the orientation of the plane. Then, concentric ellipses may be drawn about the central star. Those that pass through a planet show the orbit of that planet under the assumption of circularity. Exozodiacal light has the potential to give us a first estimate of the orbit of each planet from a single image.

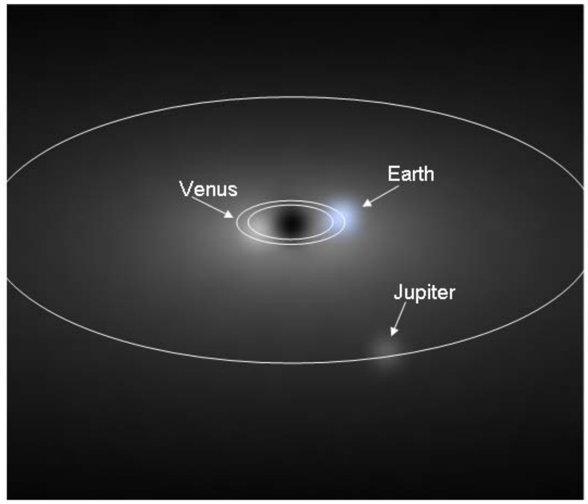


Figure 3: The exozodiacal light can pinpoint the inclination of the system and therefore the orbits can be immediately determined. This image shows a simulation of a hypothetical system with three planets – Venus, Earth and Jupiter. The exozodiacal light has total brightness equal to our own, but has been made more spatially extended.

In addition to aiding our understanding of terrestrial planet characteristics, the rest of the exosolar system is interesting in its own right. Observations of giant planets and debris disks or exozodical light will tell us about the mechanisms of planet formation and the evolution of solar systems.

We believe starshades are the best technique for doing these observations because:

- Starshades have 100% throughput for the planet light.
- Starshades create no noise in the field that could interfere with planet observations.
- Starshades have no outer working angle, enabling observation of the whole system at once.
- Starshades are passive and require no wavefront control, providing very high throughput on the telescope and enabling observations such as polarimetry and time-variability that would be impossible otherwise.
- Starshades work at >100% bandwidth at once, allowing simultaneous multi-color observations or very efficient detection of exoplanets.

The starshade's capabilities are just beginning to be explored. Ideas on using starshades to observe AGNs, blazars, bright inner cores of galaxies, and other high contrast regions, are being formulated. The starshade is also an extensible technology. Because the starlight suppression is separated from the telescope, the telescope can make use of segmented mirrors. In the near term, this means that starshades allow more cost-efficient primary mirrors to be used for terrestrial planet imaging. In the long term, as launch vehicle diameters require the use of deployable telescopes, starshades can still be used to fulfill future astronomical goals such as Lifefinder and PlanetImager, by using multiple starshades with an array of telescopes flying in formation. The starshade is a technology with a future.

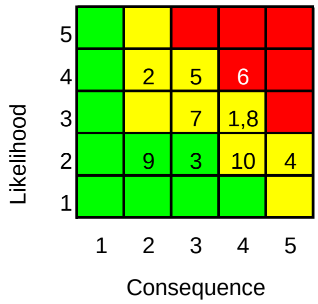
III. Starshade Technology Development

The technology development needs of a program can be quantified in terms of risk. By assessing the technical risk of starshades, and analyzing the most probable mode of failure, we can chart a program towards mitigating these risks. The top 10 technical risks for starshades as assessed for the NWO project are shown in Table 1. The risk level is shown in Figure 4, along with the definitions for the likelihood and consequence scale.

Table 1: The Top 10 starshade Technical Risks assessed for the NWO Project

Category	#	Technical Risk	Likelihd.	Cons.	Risk Level
Starshade Optical Performance	1	If the starshade simulation is inaccurate due to optical complexity of the starshade, then on-orbit performance may be significantly worse than predicted	3	4	25
	2	If, due to higher fidelity analyses, the starshade requires more perimeter control than can be accommodated in the current design, then the starshade will have to be modified	4	2	20
	3	If light scatters off the starshade due to inadequate membrane & edge control, then it may overwhelm planet light	2	3	13
Starshade Deployment and Shape Maintenance	4	If the starshade does not deploy due to deployment design complexity, then the mission is invalidated because we cannot occult target stars	2	5	29
	5	If the starshade deployed shape does not meet requirements due to manufacturing errors, then its optical performance will degrade significantly	4	3	25
	6	If the starshade deployed shape does not meet requirements due to launch or L2 environmental impacts, then its optical performance will degrade significantly	4	4	32
	7	If the starshade membrane loses opacity due to environmental impacts of launch L2, then starlight may leak and overwhelm planet light	3	3	18
Trajectory and Alignment Control (TAC)	8	If the TAC does not have sufficient control authority due to complexities in the software algorithm, or operations, then mission science return may be reduced or delayed	3	4	25
	9	If, due to higher fidelity analyses, the TAC sensor requires better performance than the current capabilities, then the TAC sensors will have to be modified	2	2	8
	10	If the thruster firing overwhelms the starshade ACS due to starshade-spacecraft dynamic coupling, then the spacecraft may go out of control	2	4	20

The risks in Table 1 include perceived risks, where insufficient information regarding the system and state of the art capabilities leads to the perception of a technical challenge. Most of these can be assessed via low-cost laboratory tests. We outline below a series of laboratory tests that are immediately implementable and that can put to rest many of these perceived technical challenges and allow us to determine if any of these technologies needs further development.



Rating	Likelihood of Risk	Rating	Consequence
5	>50%	5	>50% Loss
4	30% - 50%	4	25%< Loss < 50%
3	10% - 30%	3	5%< Loss < 25%
2	1% -10%	2	0%< Loss < 5%
1	< 1 %	1	0% Loss

Figure 4: Deployment is the starshade's high risk item. Our development roadmap will mitigate this risk.

Tests for Starshade Technology Development, in order of ease of implementation (and therefore cost):

- **Spacecraft dynamics modeling**: model spacecraft and starshade payload dynamics to determine if thruster-induced jitter will be a significant issue for spacecraft control
- **TAC Sensor limit**: research and validate the state of the art for candidate sensor technology as applied to the TAC. An astrometric sensor is mounted on the starshade and a shadow sensor on the telescope. Both the astrometric sensor and the shadow sensor requirements need to be assessed against state of the art to determine technology development needs.
- **Membrane Optical Properties**: produce and test samples of candidate starshade membrane materials for opacity, uniformity, reflectivity, and environmental durability to determine whether technology development is needed.
- **Edge Scatter**: produce and test samples of candidate starshade edge materials for edge scatter to determine whether light scattered from the edges of the starshade will be an issue that needs technology development; as this currently is an edge thinness issue, this will also test the state of the art of **Thin Edge Manufacturing**.
- **Starshade skeleton deployment**: once the baseline deployment method has been designed, build a mock up of the skeleton (minus starshade membrane) of the deployment mechanism to determine if the deployment can deliver the required edge shape.

All of these tests (except for the skeleton deployment) are simple and inexpensive. We show, as an example, the assessment flow process for part of the Membrane Optical Properties test. Using our baseline membrane material (the JWST sunshield Kapton), this test answers the question of whether the Kapton has enough opacity to allow less than 1 part in 10^{10} of incident UV-Vis light through our current design of 3 layers. Figure 5 illustrates the testing process and an approximate timeline to answer this question.

After the completion of these technology assessment tests, we will develop a more complete Starshade technology roadmap. Currently, based on the results of our ASMCS study and of work over the past 4 years, we have developed a starshade technology roadmap leading to TRL 6 of the starshade payload package, shown in Figure 6. There are 3 top-level development areas for the starshade: Starshade Optical Properties (Lo 2007; Glassman 2007), Starshade Precision Deployment and Shape Maintenance (Dailey 2008), and Trajectory and Alignment Control (Noecker 2007; Leitner 2007). We discuss each of these development areas in more detail below.

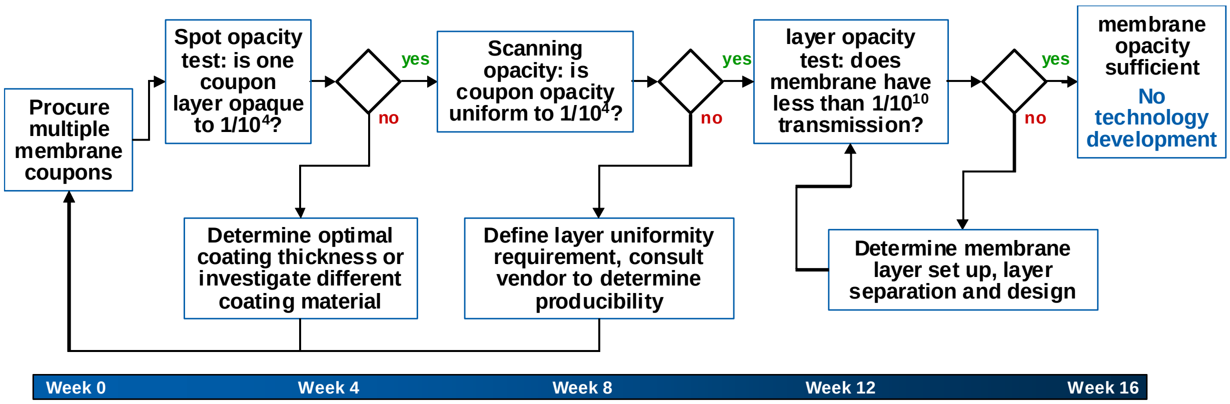


Figure 5: Four months of testing can answer a fundamental starshade technology question: is our baseline material black enough? Much of the starshade's technology can be assessed with these types of simple tests.

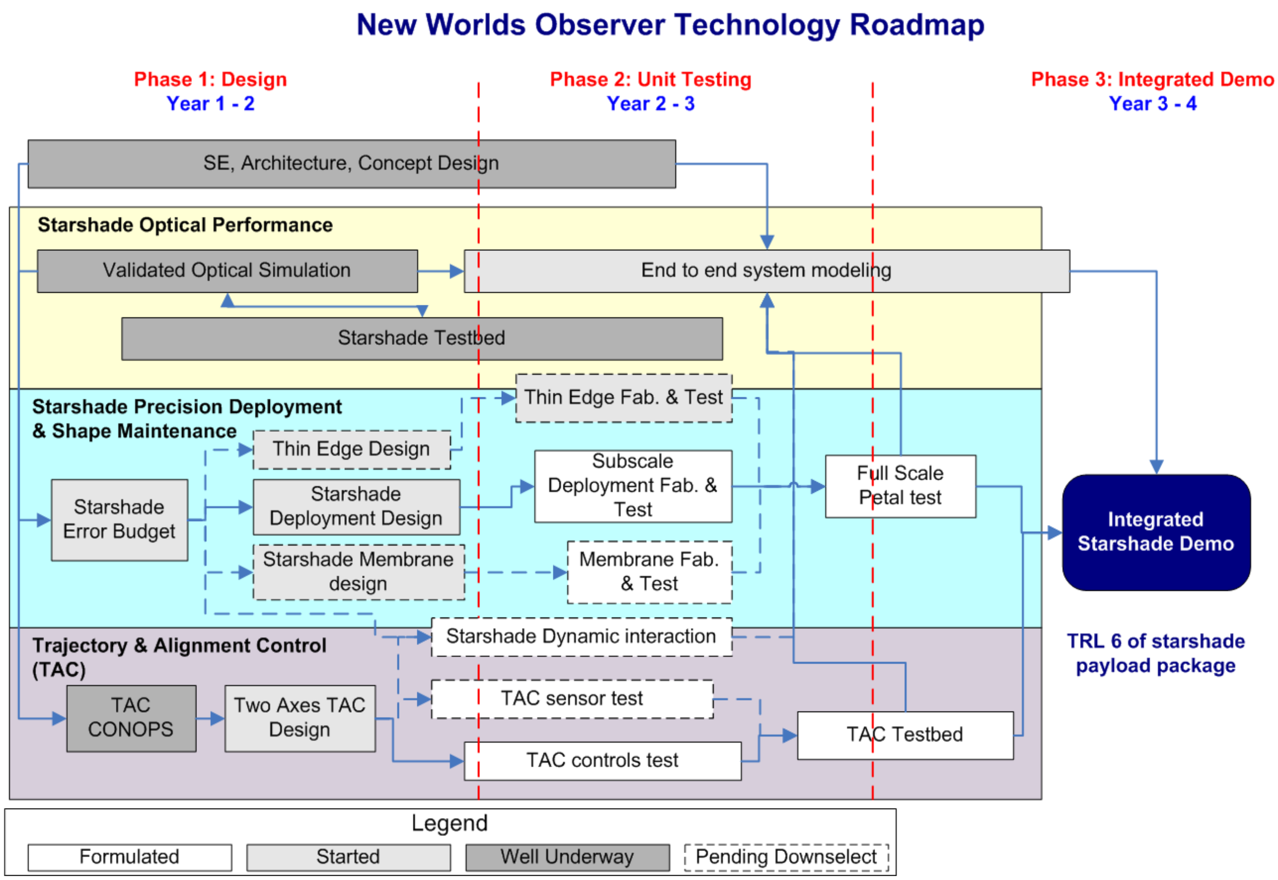


Figure 6: Starshade Technology Development Roadmap. The dotted boxes show starshade technology items that may be retired pending laboratory tests to determine development needs. Under the NWO program, many of these tests have been started.

Starshade Optical Performance

The modeling and verification of the NWO system and the starshade in particular is critical to ensuring that the starshade achieves the performance required to meet the science goals. The starshade's optical performance is the most critical area that we need to model and validate. The starshade operates in the Fresnel regime and is essentially a diffractive optic. These two factors make the starshade modeling task different from most optics currently modeled by standard optics codes. Four independent codes have been developed to the author's knowledge, and cross checking between the codes has already validated their top-level accuracy. Two codes in particular, developed by NGAS and CU, have been extensively cross checked. In addition, a thorough validation of the models with laboratory results is critical; two testbeds have been set up at NGAS and CU for this purpose. The testbeds employ different optics and very different sources: the NGAS testbed uses an artificial, white, laser source while the CU testbed (located at National Center for Atmospheric Research) uses the sun as the light source.

Table 2: Requirements and Corresponding State of the Art for Starshade Optical Performance

Requirements	State of the Art
Set of *shape* requirements that can be applied to development of designs for shape maintenance and precision deployment.	Influence of shapes on contrast has been derived on a term-by-term basis only.
Set of *edge* requirements that can be applied to precision-deployment and stray-light development.	Edge scatterometer testing demonstrated at GSFC in 2008.
Verification that the model predictions and testbed lab demos produce the same results.	Lab demos match models to the noise floor of the current beamlines.
Full observatory error budget.	Only a term-by-term error budget exists, not yet integrated.
Plan to verify that the starshade structure meets the shape and edge requirements.	Plan to use overhead photogrammetry and edge-scatterometer testing.

The tasks in this development area involve modeling the precise performance of the starshade, correlating the models with testbed results, deriving requirements that the hardware must meet, and creating a plan to verify that the requirements were met (Table 2). The requirements derived here will apply to several of the other technologies being developed including shape control, precision deployment, and stray-light control. Most of this work will involve running existing code and improving the code to model the optical performance of the starshade. These predictions will be compared with results from the testbeds showing the performance of sub-scale starshades. We will also integrate models of the starshade structure into our analysis, using existing and accepted structural-analysis code packages such as Nastran. Another part of this task is to develop a verification and validation plan to confirm that the starshade will meet the stated requirements. In this plan we will describe the verification methods, sets of tests, models, demonstrations, analysis, etc. that we believe will adequately verify that the requirements were met. In this plan we will also describe the verification levels; such as: system, segment, and element, and we will also describe the verification activities/events for each of the requirements.

Starshade Precision Deployment and Shape Maintenance

The shape of the starshade is what creates the high level of suppression of the target star. In order to maintain this suppression, the starshade must correctly maintain this shape. We have been working on designing a deployment method that will fit into the launch vehicle size and mass requirements, deploy to the required shape, and maintain its shape to the required tolerances despite the various possible error sources. Our design philosophy has been to use existing parts to minimize the required technology development; however, putting the parts together into a starshade system will require significant development and validation work. The requirements for this technology development effort and state of the art level are summarized in Table 3.

Deployment of the starshade is our most significant technology development area. The simulation work described above will enable us to define of the tolerance of the deployed shape to various error sources. These tolerances will then dictate the design of the starshade deployment and shape-maintenance mechanisms. As an illustration of the complexity of this issue, we list the structural-mechanical factors that can potentially affect the starshade shape and that we considered in creating our baseline design:

1. Mechanical piece-part manufacturing error
2. Mechanical assembly errors
3. 1 G assembly shape verification error
4. Launch Shift due to e.g. launch acceleration
5. Deployment repeatability errors
6. Thermal distortion errors
7. On-orbit spacecraft dynamics - jitter
8. Coefficient of Moisture Expansion errors
9. Contamination errors

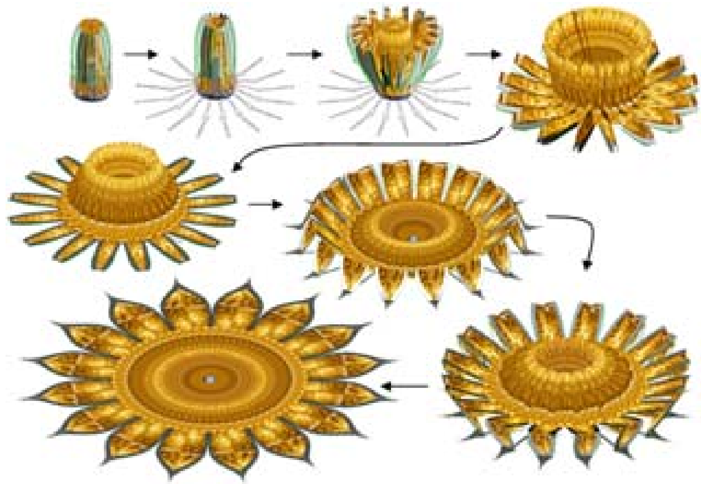


Figure 7: The stowed starshade has a high compaction ratio to fit inside an EELV launch vehicle. The starshade deployment uses a single powered mechanism for each petal.

The baseline starshade design (created to meet the requirements as we currently understand them) uses three fundamental parts: 1) a solid edge that maintains the required shape and minimizes scattered light (see next paragraph for scattered-light discussion), 2) an untensioned Kapton blanket that makes up >80% of the starshade surface, and 3) a high–heritage, telescoping-boom deployment system that is the only powered mechanism used to deploy the starshade. Our current best starshade deployment design is shown in Figure 7.

Table 3: Requirements and Corresponding State of the Art for Starshade Precision Deployment and Shape Maintenance

Requirements	**State of the Art**
Maintain specified shape within the tolerance requirements derived from the starshade optical-performance models.	Deployable rigid panels for edge control.
Fit into LV fairing and deploy to the specified shape.	Preliminary design with mass and volume margins.
Sunlight reflected from the starshade's edge shall be >30 mag as seen by the telescope.	Unknown. There are no models or measurements to determine whether an existing technology can achieve this level of performance. Pending assessment as part of technology-development roadmap
Earthshine, Moonshine, and any other stray light reflected off the face of the starshade in the direction of the telescope shall be >30 mag as seen by the telescope.	Preliminary calculations show reflected light not an issue; CONOPs avoids geometries with starshade-face scattering.

The operations concept for the starshade calls for a nominal 90 degree (sideways) or more orientation to the sun, so that the side of the starshade facing the telescope is never illuminated.

The sunward edge of the starshade, however, will be illuminated by the sun. We feel that this is a tractable issue. The starshade will be located 10,000's of km from the telescope, so even a brightly-lit edge will scatter very little light into the telescope aperture. The illuminated edge produces a small amount of extra light at the IWA in the science image; at worst, a narrow arc of pixels will have a higher noise floor than other pixels. To mitigate this risk, we have designed the starshade edge to have a radius of curvature ~100 microns which minimizes the area that could scatter light in the direction of the telescope. We are testing these edges in the Faust scatter lab at GSFC.

We continue to consider multiple designs for the starshade deployment. We will downselect to one design once we have a better idea of the requirements and which design best meets those requirements. Potential offramps include more stable but more massive designs, which may require more capable launch vehicles and/or fewer targets visited in the mission lifetime.

Trajectory and Alignment Control

Our baseline starshade TAC system has two hardware components: the shadow sensor and the astrometric sensor. These sensors work in conjunction to place the starshade within the 1 m final alignment box required for high-contrast imaging at 10^{10} suppression. The shadow sensor provides high-precision alignment measurements while the telescope is in the shadow of the starshade, enabling highly accurate alignment control to the center of the shadow. The major uncertainty needing verification is diffraction at the starshade producing the spot of Arago under the assumed conditions. If this works as predicted, the method of sensing should be simple and routine, though algorithms to estimate the off-axis position in the shadow using instrument data must be developed and validated.

Table 4: Requirements and Corresponding State of the Art for Trajectory and Alignment Control

	Requirements	**State of the Art**
Shadow Sensor	Target star magnitude limit ~ 7	Within state of the art; validate control algorithms
	Sensitivity= 0.5 mag	Within state of the art; validate control algorithms
	Noise floor= 0.071 mag	Within state of the art; validate control algorithms
	Measurement interval: 50 sec	Within state of the art; validate control algorithms
Astrometric Sensor	FOR: 45° to 135° from the sun	Within state of the art
	FOV: 1 square degree	Within state of the art
	Sensitivity: 12 mag in V band	Within state of the art
	Astrometric accuracy: 10 mas	In development: the USNO JMAPS instrument

The astrometric sensor guides the trajectory of the starshade from one star to the next. Useful for long slew maneuvers with only faint catalog stars ($m<12$) as a reference, the astrometric sensor helps reduce the reliance on frequent DSN contact and mandatory zero-thrust periods. This sensor is also useful for fine guidance to the onset of shadowing, which requires finer accuracy than DSN can provide. This is a versatile sensor filling a critical "middle range" of precision and FOV.

The requirements for the TAC are listed in Table 4. While most of the requirements for the sensors are well within the state of the art, there is not an existing, TRL 6 instrument that can meet all the requirements. For the astrometric sensor, an existing Ball star tracker approaches, and may be able to meet, the 50 mas "accuracy" requirement and meets all the other requirements. The USNO JMAPS design is believed to be capable of 5 mas (1σ) and is scheduled for a LEO mission in 2011. A prototype instrument can be tested in the Ball star tracker facility for differential-astrometry tests. We will form a budget for instrument and facility errors and use experimental data to validate the performance budget.

If state of the art technology does not meet the requirements for the shadow sensor, a potential offramp is to use longer-wavelength light that produces a larger signal. Other designs, such as outrigger cameras, can be used to extend the baseline for shadow sensing at the expense of added complexity in deployment and pointing control. For the astrometric sensor, redesign of the sensor may be needed depending on which requirement was not met. In addition, beacons on the starshade can be used to allow the telescope to search for the starshade and direct it, at the expense of reduced general astrophysics observing time since the telescope would need to be more involved in the alignment process.

If the TAC control algorithms leave more than the allowed position ambiguity during alignment, more complex algorithms incorporating historical data during maneuvering may need to be implemented. In addition, more sensors such as the outrigger system or data from science instruments such as ExoCam may be used to bridge the sensor gap. The impact of these offramps is increased algorithm complexity, increase verification cost and risk for those algorithms, and possibly increased Command &Data Handling (C&DH) complexity.

Electric Propulsion

We note here that for NWO, the NEXT electric propulsion is baselined as the primary thruster for retargeting maneuvers. While funded independently, additional lifetime testing of the NEXT thrusters will validate the engine for use on the NWO project. NEXT technology development is continuing under the In Space Propulsion Technology (ISPT) project, with the objective of bringing key system components to TRL 6 in FY2009. NWO technology budget will be allocated to a) continue thruster long-duration testing to determine thruster lifetime capability and b) execute NWO-unique risk reduction tasks.

If the NEXT project under ISPT fails to achieve adequate technology readiness, then the NWO project could incur additional costs and risks to implement NEXT. The mission could baseline alternate EP systems (BPT-4000, NSTAR, or XIPS-25) with the impact of reducing the number of target visits since alternate systems have lower available throughput or fuel efficiency

Development Budget and Schedule (in $M)

Table 5 shows the current development budget and top-level schedule for the four areas of development.

Table 5: Top level development budget and schedule for the four technology areas needed for Starshades, in $M

Technology Development Activity	2010	2011	2012	Total
1. System Modeling and Verification	$2 M	$3 M		**$5 M**
2. Starshade	$3 M	$10 M	$14 M	**$27 M**
3. Alignment Control	$1 M	$4 M	$5 M	**$10 M**
4. Electric Propulsion (for NWO)		$2 M		**$2 M**
Total	**$6 M**	**$19 M**	**$19 M**	**$44 M**

With a 3 year development effort and ~$44M dollars, we believe we can bring the starshade to TRL 6. With an additional year of effort, an integrated demonstration unit, as shown in our roadmap, can be produced and validated. The starshade is a fundamental enabler of much future science in the field of exoplanet discovery and characterization and high-contrast imaging and spectroscopy.

IV. References

The NWO ASMCS Study Report & Appendices are at: http://newworlds.colorado.edu/

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