Jet Propulsion Laboratory
California Institute of Technology

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TECHNOLOGY DEVELOPMENT FOR EXOPLANET MISSIONS

Technology Milestone Whitepaper

Starshade Stray Light Mitigation through Edge Scatter Modeling and Sharp-Edge Materials Development

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1. Objective

In support of NASA's Exoplanet Exploration Program and the Technology Development for Exoplanet Missions (TDEM) component of NASA's Strategic Astrophysics Technology (SAT) solicitation, this whitepaper explains the purpose of the TDEM Milestone for the evaluation of edge scatter from starshades, specifies the success criteria against which the milestone will be evaluated, describes the differences between the test implementation and future flight implementation of the starshade, and outlines the milestone demonstration procedure. The tasks identified in this white paper are consistent with the scope of initial proposal submitted in March, 2013, updated as much as feasible to reflect new data and research results.

2. Milestone Description

Technology milestones serve to gauge the developmental progress of technology for a space-based mission and the mission's readiness to proceed from pre-formulation to formulation. The completion of the milestone described here is to be documented in a report by the Principal Investigator and reviewed by NASA HQ.

The following milestone addresses the mitigation of broadband light from the Sun scattered off the starshade edge into the telescope. This milestone will include simulation development and sample testing to determine if there is a hardware implementation that meets requirements derived from the simulation.

The milestone is stated as follows:

> *"Develop a scattered light simulation and use it to derive requirements for the edge radius of curvature and scattering properties;*
> *Build and test at least two sharp-edge samples to evaluate the feasibility of flight-compatible materials being fabricated to the derived requirements and how well such a sample performs compared to the predictions of the simulation."*

We recognize that diffraction has been identified as a significant component to the stray light from a starshade edge by Martin et al. (2013), providing an equivalent contribution to the scattered light for small radius of curvature edges. However, we have not included this in the scope of our milestone directly as it was not in the original proposed scope for the simulation development. To the extent possible within our available budget and schedule, we will include the diffraction component in the analyses, and to the extent that it is present, it will be measured in the test of the sharp-edge samples.

3. Background and Current State of the Art

An external occulter mission (or starshade) is one of the methods being studied to be able to detect and characterize extra-solar planets around nearby stars. Several teams are studying the requirements for such a mission and identifying the technical challenges that must be addressed if such a mission were to be undertaken. The Exoplanet Exploration Program (ExEP) released a prioritized list of the technical challenges facing a starshade-based mission [Lawson et al. 2013], the number one challenge being control of stray light. This is because the contrast ratio between the planet and its host star is ~25 magnitudes [Turnbull et al. 2012] and the potential target stars range in brightness from magnitude 2 to 7. Thus for the faintest target stars, the planet brightness would be ~32 magnitudes.

One source of stray light is from the parent star leaking past the starshade. This is addressed by the design and construction of the starshade and is the focus of other technology development efforts. A second contribution is from the light from our Sun that scatters from the edge of the starshade. This must also be controlled so that it doesn't swamp the light of the target exoplanets. Because of the geometry of the system, only the very edge of the starshade is visible to both the Sun and the

Telescope (see Figure 1). However since the starshade is 10s of meters in diameter, this can still add up to a large area. Controlling sunlight scattering from this edge, through a combination of making the edge narrow and making it black, is the focus of this TDEM.

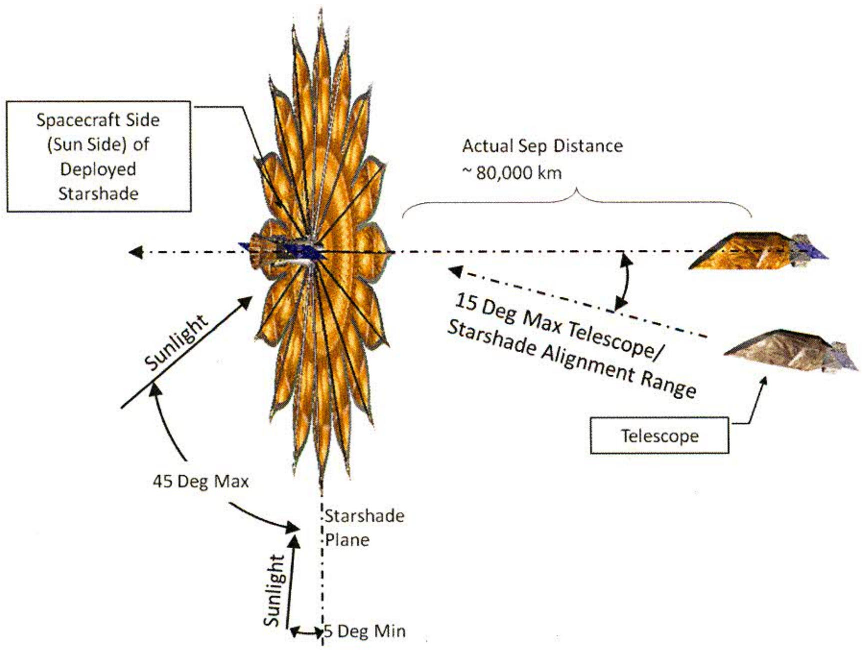

Figure 1: The geometry of the starshade system ensures that only the edge of the starshade is lit by the Sun and also visible to the telescope. The angles shown above are typical operating ranges for a starshade mission.

Our initial TDEM proposal was based on modeling and analysis published in two papers [Arenberg et al. 2007 and Casement et al. 2012] which suggested that a modest edge radius of curvature (25 – 100 microns) would be sufficient to reduce the scattered light to an acceptable level for a Flagship mission (such as the one described by Turnbull et al. 2012). More recent analysis [Martin et al. 2013], published after our submission, suggests that diffraction is the dominant contributor to the stray light originating from the Sun and that scattered sunlight would drive the edge radius of curvature (ROC) down to a few microns. The modeling results are significantly different between the two studies. Casement et al. show that the scattered light provides a reduction of Solar flux by ~57 magnitudes using an edge ROC of 50 microns and the scattered light properties of Graphite Polycyanate, with the BRDF (Bidirectional Reflectance Distribution Function) as given in Figure 2. Using a 1% Lambertian surface results in a reduction of Solar flux by ~ 61 magnitudes. This disagrees dramatically with the Martin et al. result which shows that the Solar flux is only reduced by ~50 magnitudes assuming a Lambertian scattering surface with 10% reflectivity and a 10 micron edge ROC. Even accounting for the difference in reflectivity used in each model (1% v. 10%, equivalent to 2.5 magnitudes) there is still a very large disconnect of at least 9 magnitudes, as our edges are also significantly thicker. By performing this work, we intend to resolve the differences between these two sets of models. In addition, we will identify materials which can meet the optical property requirements indicated from the model and can do so after surviving launch and exposure to the space environment. Testing of sharp edged samples performed in this work will help validate the models.

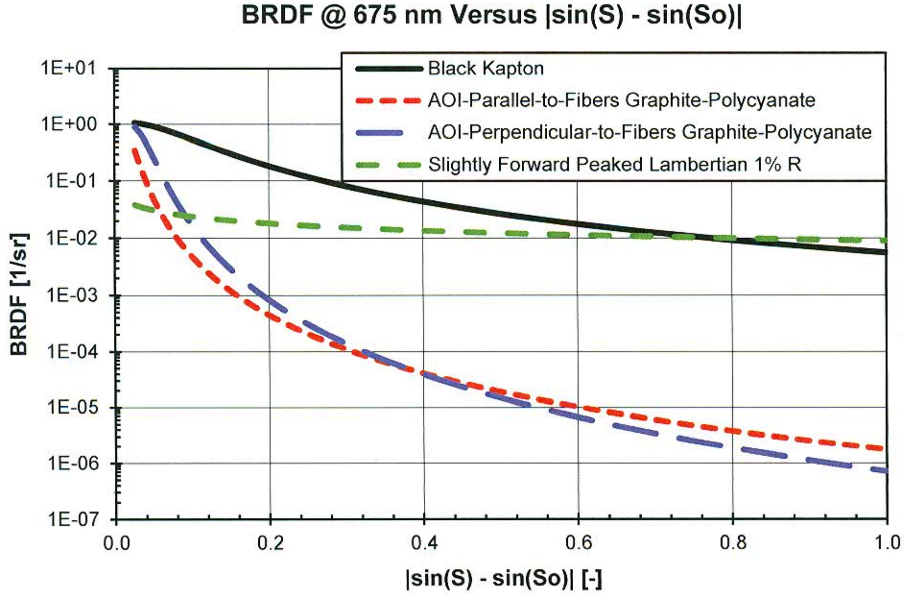

Figure 2: BRDF for common materials used in initial starshade stray-light modeling. S is the scatter angle and So is the angle of incidence.

For all of our analyses for this TDEM, we will assume the New Worlds Observer architecture, as documented by the ASMCS study [Cash et al. 2009]. We recognize there are many variations of a starshade mission which have been or are currently under study (such as Exo-S). However, to provide the best value under this study, we will use our NWO mission design since it is readily available and we believe scaleable to other architectures based on, for example, separation, total edge length, and edge ROC.

This work will build on the ASMCS results [Cash et al. 2009] and additional work on the NWO architecture to address the (at the time) unconsidered aspect of the mechanical starshade structure, the edge scattering properties. The Martin et al. assumed an Exo-S architecture which also requires the edge to be flexible for deployment. For this study, we are only including rigid body (geometric) contributions to the stray light problem. We are also not limiting ourselves to highly flexible materials for selection as the NWO deployment architecture does not require any flexibility to the edge. We expect that many materials would ALSO satisfy the Exo-S highly flexible edge requirement with appropriate fabrication and handling techniques, but to limit our evaluation to materials that meet that specific flexibility criterion is inconsistent with our proposal and with our overall technology development approach.

4. Success Criteria

The following are the required elements of the milestone demonstration. Each element includes a brief rationale.

a. Develop an independent stray light model, simulating a Flagship-class starshade exoplanet characterization mission. Nominally, the ASMCS New Worlds Observer (NWO) mission parameters [Cash et al. 2009] will be used, but results could be scaled to other starshade mission architectures. Document the limitations and accuracy of said model.

Rationale: The previous model [Casement et al. 2012] developed at NGAS in TracePro required many scaling factors to bridge the large dynamic range of the model, from microns to megameters. An addi-

tional model developed at JPL [Martin et al. 2013] results in widely different predictions. An independent model will be developed by Photon Engineering (PE), recognized as experts in stray light modeling, to evaluate the stray light of the system. The model developed by PE will be in FRED, a commercial stray light software package. A CAD model (shown in Figure 3) is used as the input to the simulation to allow precise representation of the hypergaussian petal shape and edge radius of curvature used in the mechanical design, rather than just an edge approximation using ellipsoids as in the original TracePro-based model. We chose the NWO architecture as our baseline as we can use an existing CAD model and it is representative of the range of current starshade architectures in development.

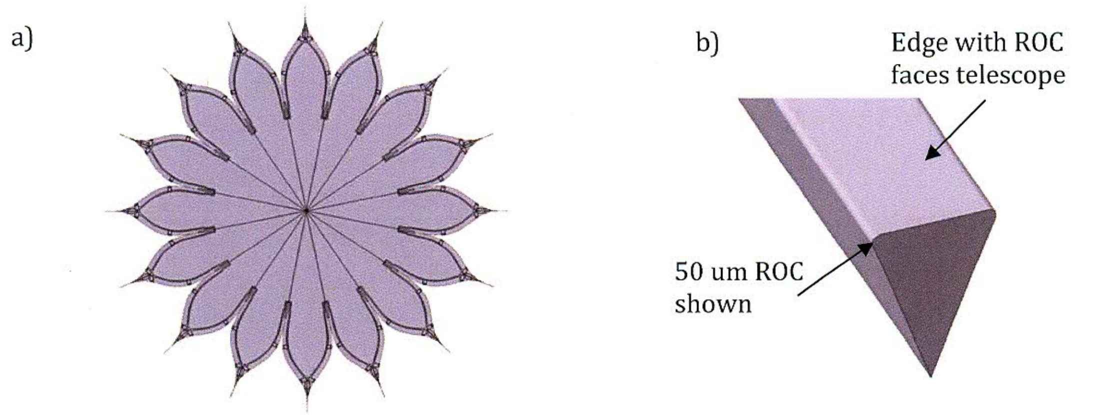

Figure 3: The starshade CAD model to be used in the FRED simulation. a) shows the full starshade model while b) shows a close up view of a tip. The radius of curvature is on the telescope-facing edges of the starshade as indicated in the figure while the back of the tip is tapered to minimize other stray light and to provide structural support. A 50 um ROC is shown in the figure.

As part of the model development process, an error analysis will be performed to estimate the accuracy of the model. This will include the numerical accuracy of the algorithm, the statistical accuracy based on the number of rays launched, and estimates of the accuracy of the input parameters, such as the BRDF of the material used on the edges, along with any other physical parameters used in the model.

Note: Details of both TracePro and FRED are available on the software websites provided in the references. The 2012 version of TracePro we used for the initial study did not at the time support importing our NWO CAD model so a solid geometry was created using the starshade shape prescription.

While the initial modeling effort does not include the impact of diffraction, our team is assessing the feasibility of adding it in, at least at an analytical level. We believe the PE model will provide a new look at this problem without many of the simplifying assumptions used by both previous models and provide a more accurate result, at least of the scattered light component.

b. From the model, derive edge-property requirements for the starshade that are needed to meet the stray light requirements. The edge properties are defined by the scattered light properties of the material (the BRDF, or how much light scatters off the material as a function of both angle of incidence and reflection) and the edge ROC (how much surface area scatters light back to the telescope). As feasible, the diffracted component will be included in the evaluation, whether as part of the simulation developed in (a) or as an added contributor using results from the JPL developed diffraction model. These will be compared to available materials to evaluate feasibility.

Rationale: The system-level stray light requirement is that the sunlight scattered from the edge of the starshade into the telescope should be fainter than the faintest target planet, which is ~32 mag [Turnbull et al. 2012]. From previous calculations [Casement et al. 2012], the amount of sunlight scattered *from the starshade into the telescope must be <1 x 10^{-25} that of the incident sunlight. Based on this top-level requirement, the required edge ROC will be derived using the scatter properties of two limiting cases, a black diffuse surface and a metallic specular surface. These are both feasible material types and are discussed as potential materials in Martin et al. The BRDF data for these typical materials are also well documented in the literature. Edge ROC requirements for additional materials will also be derived, as possible, based on the availability of existing BRDF data.*

Inclusion of the diffraction component should be purely additive based on the Martin et al. analysis. If the diffraction component is beyond the scope of the simulation development in (a), JPL has offered to provide a run of the NWO architecture using their modeling techniques to provide an estimate of the diffracted component of the stray light.

c. Evaluate optical and mechanical properties of potential edge materials and identify at least two candidates for testing.

Rationale: A wide range of possible materials (including substrates, coatings, treatments, etc.) will be evaluated for initial feasibility based on the available published data for both optical (scattering) properties and mechanical properties in terms of ability to be cut to shape or coated onto an edge, depending on the approach. The material selection is informed by the breadth of flight hardware experience to ensure that the materials are highly likely to be suitable for use in space. Thermal properties of the material are particularly of interest, given the large variation in incident radiation on the different parts of the starshade edge. The candidates will be selected based on all these properties in order to have the highest probability for future flight qualification while also providing the best optical performance.

d. Perform detailed optical testing of candidates selected in step (c) both before and after a limited set of environmental exposure to evaluate their suitability for flight and the potential degradation of their optical properties. The environmental exposure tests, consisting of thermal cycling and a subset of the abrasion testing required for material and coating flight qualification, will be performed on simple, flat test coupons to simplify the environmental testing and leverage standard test procedures. The BRDF of the coupons, both pristine and exposed, will be measured at a high angular resolution covering the relevant angles of incidence and reflection for the NWO architecture, at three wavelengths of interest.

Rationale: The initial survey and evaluation of candidate materials in step (c) will provide likely candidates to meet the optical and mechanical requirements for the starshade edge. Coupons of the selected materials will be fabricated to allow some preliminary environmental testing. Any selected material will require flight qualification; the stow/deploy cycle for the starshade as well as the space environment will likely change the performance at end of life. While not a full qualification, this initial step towards that goal will provide both detailed BRDF measurements at multiple wavelengths both before and after environmental exposure to provide data for updating the stray light model and evaluating how much degradation is expected at end of life. The BRDFs will be measured at 6 angles of incidence to cover the range of sun angles and over 180 degrees to cover the range of edge orientations to the telescope. Proposed wavelengths for testing are 488 nm, 633 nm, and either ~550 nm if available in our timeframe or 3.39 microns to evaluate the out of band stray light from the material. The 3.39 um measurement would be useful to inform some methods of the starshade alignment procedure but is not directly related to the primary mission so is lower priority if the mid-wavelength laser is available at the time of testing.

e. Build two sharp-edge samples using the best candidate material(s) identified in step (d) and measure the distribution of scattered light (equivalent to a BRDF) from the edge.

Rationale: Fabricating and testing a sharp-edge sample of at least one, and preferably two, high-probability candidates will help to anchor the model predictions as well as start to determine the feasibility of manufacturing sharp edges with the selected material. The samples will be straight edges, but built as close to flight like as possible, with an edge length of at least 3 cm to be sufficiently oversized compared to the 3 mm beam size to avoid any effects from the end of the sample. Figure 4 shows the flight edge architecture developed in the scope of the ASMCS study [Cash 2009] and a cartoon of what the samples might look like relative to this design. This is potentially done in parallel with step (d), within the funding limitations. The test approach for this is not trivial given the need to strictly control the scattered light and to accurately scale the result for the small angular collecting aperture of the telescope. The detailed measurement approach will be developed as part of the TDEM activities. Small-scale edge testing has been done using relatively short separations [Martin et al. 2013], but it is unclear how well the scattered light is controlled in the system. We will leverage this expertise as well as the experience of our team of experts to make independent measurements that will provide confirmation of the test results using a more traditional scattered light measurement technique.

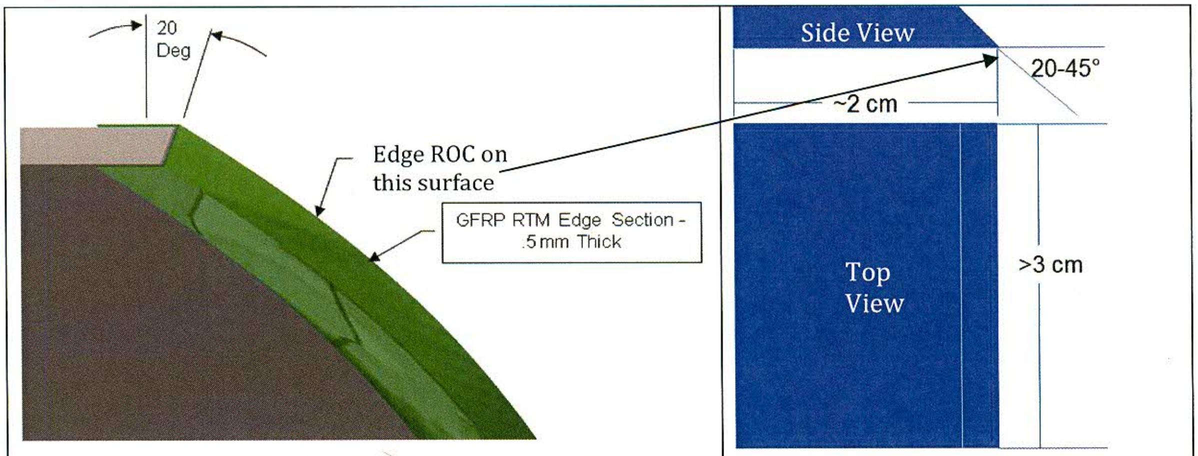

Figure 4a: Edge concept design for NWO developed under the ASMCS work. Notional concept is a U-channel construction around a lightweight honeycomb panel. The notional edge in this design is a Graphite Fiber Resin Polycyanate (GFRP) made with a Resin Transfer Molding (RTM).	Figure 4b: Cartoon of sharp edge sample. ROC on the sharp edge will be derived. Thickness of sample is material dependent but likely ~1mm.

f. Update the stray light model with revised optical properties for the identified candidate edge materials as estimated for end of life step (d) and measured in the sharp-edge sample testing step (e). Refined edge ROC requirements to achieve the mission stray light requirement will be derived from the model using the measured properties of each of the tested materials. If feasible, calculate the distribution of scattered and diffracted light in the image plane from the model.

Rationale: The results from the scattering measurements from both steps (d) and (e) will be incorporated into the model to provide more refined predictions of scattered light than were possible with the standard BRDF used in step (b), allowing new edge ROC requirements to be derived for each tested material. An estimate of the diffracted light will also be calculated, if this calculation is shown to be feasible in the first modelling step (a).

The model is planned with a nominal telescope design, which will allow evaluation of the distribution of scattered sunlight in the image and the impact on the mission performance. This can help refine the specific impact of scattered sunlight on the ability to detect planets and therefore refine our system-level stray light requirement.

If the final derived edge ROC requirement is less than the nominal value of 50 µm, the ability to manufacture such edges with the selected materials will also be evaluated.

5. Differences between Laboratory Demonstration and Flight

The model will represent the flight environment and NWO Architecture as closely as possible within the limitations of model accuracy. The detailed deviations from the flight system, if any are required due to the large range of scales represented in the model, will be fully documented and described in the quarterly report after they are defined. At this time it is unclear if the diffraction component described in Martin et al. can be included in the FRED-based model. This will be evaluated by the team and included if feasible. If it is not, we will consult with Martin et al. to use their analytical diffraction model to estimate the effect of diffraction in our architecture and evaluate the applicability and scaling factors to our model.

The scattered light testing will be initially done on flat samples in the lab with limits imposed by the available detector and angular resolution of the test facility. Measurement accuracy and precision estimated for the current set up is better than 5% over all angles. Modifications to the method of collecting the BRDF to more accurately represent the flight system are being considered, including restricting the incident light to a slit rather than a circular beam to enable higher accuracy of angular data to be collected. We will test at three wavelengths (488 nm, 633 nm, and either ~550nm or 3.39 microns depending on test availability) to cover the full spectral range of a likely instrument suite. In addition, limited measurements are planned at a longer wavelength to evaluate the impact of stray light on one of the potential alignment options, a camera that images the spot of Arago at a wavelength in the infrared where the starshade is no longer as effective at suppressing it.

The ultimate objective is to build a flight-like edge piece of the selected material for a true "3D" test. This will be as flight-like as we can make it, but will by necessity be only a very small piece of the edge and will be straight, without the precise edge shape required for the starshade. If the chosen material involves a coating process, the process will likely deviate from flight and be done manually, as the size of the sample will be small rather than the large quantity of edge pieces required for a flight starshade. The repeatability of fabrication processes will not be part of this study.

This limited study is focused on the optical and environmental performance of the selected materials. The ASMCS study [Cash 2009] went into great detail of the mechanical architecture and system deployment for the NWO architecture and forms the basis of our selection criteria. Due to funding limitations, we will be looking carefully at the ability for any treatment to maintain the edge shape and edge ROC, but we will not be performing a detailed evaluation of the thermal properties of the material or the thermal management required for an edge made of the material. An initial assessment of manufacturability and handling complications based on the extensive experience of the engineering team at NGAS will be included in the ranking assessment of different material options. Thermal cycling to evaluate material durability is planned and basic thermal properties will be used in the initial screening process to ensure the material won't be too fragile under thermal gradients. Since there are many ways to mount this edge and control thermal impacts via substrates or other tools of the trade, the required detailed thermal modeling is beyond the scope of this study. A critical follow-on to this work will be an evaluation of the material to maintain the edge shape in the flight thermal environment. Finally, we are not putting any restrictions on material properties which would be driven by the starshade stow / deployment method (such as a specific degree of flexibility) for the purposes of identifying candidate materials, as there are several deployment and stow options which have been previously studied. Such properties will influence the ranking of materials for further study in steps (c) and (d) described above, but will not a priori eliminate materials from consideration. Future studies should evaluate the material applicability to a variety of stow / deploy concepts.

6. Milestone Validation Procedure

The starshade system will be translated into a full stray light model by Photon Engineering using the deployed CAD model of the NWO starshade and system architecture. Using two bounding material options and a nominal 50 μm edge ROC, a baseline stray light performance metric will be calculated.

After a variety of materials are identified as edge candidates, the properties of these materials, both mechanical and optical, will be used to rank order them to select at least two high-probability candidates for further test. Once identified, several thin flat coupons of the candidate materials will be fabricated. Half of the coupons will undergo a limited set of environmental testing appropriate for flight qualification of the selected materials. These will include (at minimum) simple durability testing and thermal cycling to ensure the performance of the proposed materials will meet optical and shape requirements after handling, stow and deploy cycles, and exposure to the space environment. These coupons, both pristine and environmentally exposed, will be tested by The Scatter Works to measure key BRDF properties at three wavelengths so that we can evaluate the environmental impact on the optical performance. Should significant degradation be observed, these values will be entered into the stray light model and the system level performance evaluated.

We will also fabricate at least two sharp-edge samples of one or two candidate materials and perform direct stray light testing on them per a process that will be developed early in the program. The measurement accuracy is anticipated to be somewhat worse than for the flat coupon measurements, but likely on order 10%. Early test concept evaluation indicates that polarization measurements should be feasible in the facility and the ability to differentiate between scattered light and diffracted light is under evaluation. If possible, measurements of both components will be made. The final test plan will be documented in the appropriate quarterly report for evaluation. The samples will be evaluated for their stray light properties, their ability to be fabricated with and to maintain the required edge ROC, and their material properties including thermal conductivity, mechanical strength, and ease of handling to evaluate suitability for use as the starshade edge. The data will be compared to the results of the stray light model (with any required scaling factors to be documented in the report).

The stray light model will be updated with the candidate material data and the results will be compared to the baseline. Effects of varying the edge ROC will be explored should the baseline ROC not provide adequate control of the stray light from the Sun for at least one measured BRDF.

7. Milestone Certification Data Package

All test data will be provided as well as any associated calculations of effective BRDF, if applicable. The model inputs and results will be fully documented and reviewed according to established Program guidelines.

The following data will be presented in a final report:

1. Initial stray light model design objectives and inputs
2. Stray light model initial results with error estimates using standard materials for edges
3. All materials (including substrates, coatings, or treatments) considered for testing, including all relevant material properties and the selection approach
4. List of properties for materials chosen for testing and rationale for selection
5. Results of environmental and BRDF testing, before and after environmental exposure, for flat samples of selected materials, including the measurement error estimates. Polarization measurements of the stray light will be included on a best effort basis.

6. Selected materials for sharp-edge samples with rationale for selection
7. The design of the sharp-edge samples
8. Measurements of the fabrication accuracy for the sharp-edge samples
9. BRDF measurements of the sharp-edge samples
10. Updated model results using the sharp-edge sample and post-environmental exposure data
11. A summary of future work required to extend this work to the next technology development milestone(s) as informed by the study; areas such as diffraction and polarization (to the extent that they are excluded from the study), the impact of thermal distortion on the materials studied, applicability of the selected materials for different stow/deploy concepts, and approaches for thermal design to minimize thermal distortion are likely candidates for inclusion.

The executable stray light model is not a deliverable, only the inputs and outputs (requires FRED commercial software). The NWO CAD model used as input to the stray light model will be made available to the Exoplanet Exploration Program office upon request.

8. Milestone Report

The Principal Investigator will assemble a milestone report for review by the Exoplanet Exploration Program and its Technology Assessment Committee (TAC). In the event of a consensus determination that the success criteria have been met, the Program will submit the findings of the ExEP TAC to NASA HQ for official certification of milestone compliance. In the event of a disagreement between the Program and the TAC, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

9. References

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Additional information on TracePro is available here: http://www.lambdares.com/features

Additional information on FRED is available here: http://photonengr.com/software/

8. Approvals

Approved/ ______________________

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