# ExoTAC Report on Starshade S5 Milestones #1A and #1B Review

May 1, 2019

A telecon review of the Final Reports for Milestones #1A and #1B for the Starshade Technology to TRL 5 Activity (S5) was held on April 29, 2019. With one unavoidable exception (Rebecca Oppenheimer), all of the ExoTAC members were able to participate in the telecon. However, all of the ExoTAC members participated in the writing and reviewing of this report.

These two related Milestones deal with demonstrating high contrast imaging with small-scale starshade masks in the Princeton University Frick Testbed, with the optics and testbed parameters chosen to provide flight-like Fresnel numbers (less than or equal to 15). This ensures that the test results can be confidently predicted to be applicable to full-scale flight systems, which could require starshade diameters in the range of 26 to 52 m. The nominal space telescopes assumed are the 2.4-m WFIRST mission (potentially leading to a 26-m Starshade Rendezvous Mission, or SRM) and the 4.0-m monolith option of the HabEx large mission study (with a 52-m starshade). For comparison, the starshade masks used in these two laboratory Milestones vary from 24.28 to 25.06 mm in diameter for #1A and #1B, respectively.

Milestone #1A requires the demonstration of 1e-10 instrument contrast at the inner working angle (IWA) in narrow band visible light, while Milestone #1B extends this required contrast to multiple wavelengths of more than 10% bandpass. The laboratory setup for Milestone #1A used narrowband 641 nm laser light, yielding a Fresnel number of 13, while Milestone #1B used four wavelengths, centered on 641, 660, 699, and 725 nm, producing Fresnel numbers between 12.2 and 13.8, as required. Testbed performance with polarized light was investigated and found to be important for achieving high contrast. The inner working angle is defined to be the angle from the optical axis to the tips of the central petals in the starshade masks, while the outer working angle is defined to extend to the end of the linear portions of the masks inside the outer mask petals, neither of which would be present in a flight configuration. Two identical apodization functions were used for the #1A and #1B masks, but with the #1B mask being scaled to a slightly larger size in order to be optimized for the longer wavelength bands under consideration.

For Milestone #1A, the results showed that the bright lobes inside the IWA are aligned with the linear polarization angle chosen, not with the rotational angle of the mask around the optical axis. When averaged around 360 degrees, the Milestone #1A result is an average contrast of 1.15e-10 at the IWA of 50 arcsec, nominally not quite meeting the requirement of 1e-10. However, the average contrast improves to less than 1e-10 for angles greater than about 53 arcsec, when averaged over an annulus of width lambda/D. Furthermore, Milestone #1A does not specify explicitly how much of the IWA has to meet the 1e-10 contrast requirement, and the results show that for 44% of the 360 degrees, the contrast is better than 1e-10 at the IWA, so it is clear that Milestone #1A has been formally met at the IWA contrast of better than 1e-10 for a significant range of angles around the optical axis. In addition, the results are presented as trying to achieve contrasts better than 1e-10, i.e., 1e-10 minus a noise of 3-sigma, in order to take noise into account. With the noise estimated to be sigma ~ 2.3% (Table 4), that means the results are presented as achieving contrasts of 1e-10 minus ~ 6.9%, or ~ 0.93e-10, which is being met at 44% of the angles at the IWA. The Milestone language does not specify a 3-sigma constraint, simply 1e-10, so the presented results of 44% at 0.93e-10 are being held in some sense to a higher standard than the formal Milestone language. In addition, Milestone #1A is met in 90% of the area between the IWA and the effective OWA of the mask (Figure 5b). Finally, the good agreement between the lab data and the vector theory shows that there is a good understanding of the sources of the remaining diffracted light. The ExoTAC therefore concludes that Milestone #1A has been met, given the lengthy analysis above.

For Milestone #1B, the results again showed that the bright lobes inside the IWA are aligned with the polarization angle and do not depend much on wavelength. The vector diffraction modeling employed shows good agreement with the testbed results for the bright lobes inside the IWA, much better than the results of a scalar model. The #1B results for the same wavelength as used in #1A, 641 nm, are different, because of the slightly larger scale of the mask used in #1B. The fraction of the 360-degree circle at the IWA that meets the constraint of 1e-10 minus 3-sigma varies significantly with wavelength: 18%, 34%, 2%, and 6%, for 641, 660, 699, and 725 nm, respectively. This degradation in performance is attributed to the broadening of the point-spread function (PSF) as the wavelength increases. However, again the contrast improves remarkably outside the IWA (about 52 arcsec), dropping below 1e-10 outside about 57 to 64 arcsec. The modeling implies that the degraded performance at the IWA is largely a result of the finite thickness and shape of the edges of the laboratory mask near the thin petal gaps inside the IWA. While the average contrast at the IWA for #1B for all angles and all four wavelengths is 1.97e-10, the fact that 1e-10 contrast was achieved at the IWA for at least a small portion of the angles at all four wavelengths implies that Milestone #1B, as worded, has been formally met. In practice, the results imply only an acceptable degradation of the desired effective IWA for the starshade concept. It is notable that the Frick Testbed operates at ambient temperature and pressure, compared to the vacuum testing available at the JPL HCIT, and scattering by atmospheric molecules plays a role in the achieved contrasts, as shown by the theoretical models employed.

We applaud the team's inclusion of MEEP modeling in understanding the Testbed results, and their ongoing efforts to use MEEP modeling, in conjunction with new mask designs, in order to better understand how the thick screen edge effects will scale to flight systems.

Overall, the ExoTAC believes that Milestones #1A and #1B have been met. We congratulate the team on their excellent efforts to advance the technology readiness levels of the starlight suppression elements in the S5 activity. Achieving these two out of a total of fifteen S5 Milestones serves as a confidence builder for the entire S5 activity.

We thank Anthony Harness, Stuart Shaklan, Jeremy Kasdin, Phil Willems, and the other S5 team members for their presentations and comments during the review.

## Exoplanet Exploration Program TAC Members

Alan Boss (Chair), Carnegie Institution

Rebecca Oppenheimer, American Museum of Natural History

Joe Pitman, Heliospace Corporation

Lisa Poyneer, Lawrence Livermore National Laboratory

Steve Ridgway, National Optical Astronomy Observatory