Hybrid Observatory for Earth-like Exoplanets (HOEE)

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NASA solicitation **80HQTR21NOA01-22NIAC_A1**

Contents

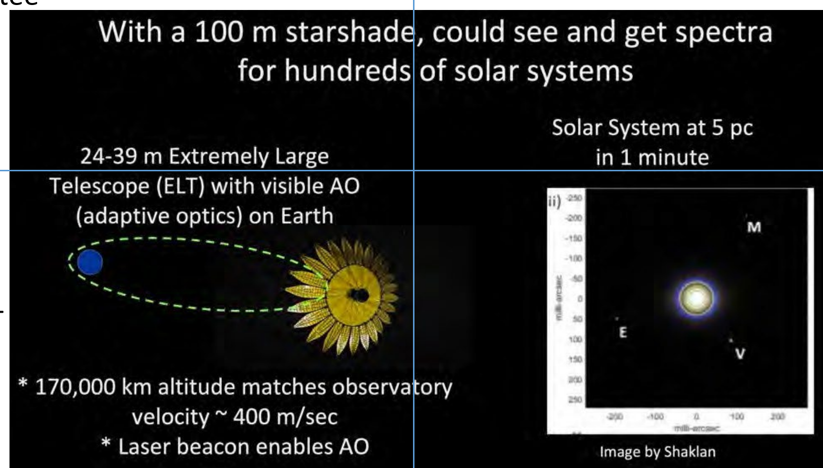
Hybrid Observatory for Earth-like Exoplanets

Innovation

- 100 m class ultralight starshade in space blocks starlight so extremely large 39 m ground-based telescope sees Earth-like exoplanets
- First hybrid observatory using both space and ground optical elements with perfectly matching velocities
- Requires 10x lightweighting compared to best available deployment
- Highest priority exoplanet science recommended by National Academy committee
- Usable with any telescope
  - on ground or in space
  - currently existing or planned for the future

Technical Approach

- Evaluate optical requirements for shape accuracy, leakage, solar reflection, rigidity
- Phase 1: Design stand-alone rigid shapes 1/10 the mass of current deployable approach meeting all requirements
- Phase 2: Develop space assembly construction
- Phase 3: Build scale models to verify mechanical rigidity:
  - Quantify implied system mass including structure and propulsion
  - Estimate scientific yield based on properties



Potential & Benefits

- Would be most powerful exoplanet observatory yet
  - Imaging an Earth in 1 minute at 5 pc distance
  - Generating spectra of oxygen and water in 1 hour
- Maximum sensitivity, angular resolution, and contrast (ability to see faint planets near bright stars)
- Demonstrate ultra-light space assembly technology for highest priority exoplanet science
- Lower cost and better performance than HabEx and LUVOIR missions
- First hybrid observatory concept with a large optical element in space and telescope on ground

Evaluation Notes

(Proposers, please leave blank)

Fig 1 Phase I Summary Chart

1 Executive summary

The Hybrid Observatory for Earth-like Exoplanets (HOEE) was proposed to solve the main technical challenge of building an ultra-light starshade for the first hybrid exoplanet observatory. The HOEE combines an orbiting starshade with a large ground telescope, with fundamental advantages over competing technologies for imaging exoplanets. It converts the challenges of optical perfection in giant space telescopes, into mechanical engineering for a passive object that works with much larger telescopes already built and operating on the ground. It is perfectly efficient outside its inner working angle (angular size of its shadow), blocking no planet light. Once built to the required tolerance, its optical performance is guaranteed. There is no need for extreme precision or stability in any optical system.

Exoplanet science is the most rapidly growing area of astrophysics today and has been a key investment area for NASA ever since the HST and Beyond report of 1995 https://www.stsci.edu/stsci/org/hst-and-beyond-report.pdf. "Are we alone?" is posted prominently on NASA's web sites, and is one of the most popular topics with the public and the press. The HOEE would address the highest priority recommendation of the Exoplanet Strategy report: observe reflected light from Earth-like planets with low-resolution spectroscopy. This light is influenced by surface minerals, oceans, continents, weather, vegetation, and atmospheric molecular constituents, temperature, and pressure. In particular it is influenced by the presence of water and oxygen, key indicators of an Earth-like planet, and evidence for the existence of life elsewhere. HOEE would help answer the questions: is the Solar System rare? Are there oxygen and water-rich atmospheres on potentially habitable planets? Is there life elsewhere? Does life require a special chance event, or is it a thermodynamic imperative, occurring wherever conditions are suitable?

Our Phase I NIAC study focused on the major challenges of this mission approach, identifying which methods are best suited to reduce mass while maintaining shape under the expected operational conditions. We refined our requirements, worked with the NASA Tournaments office to find new concepts through GrabCad.com, we sponsored a student competition through the Society of Physics Students, and we developed our own inflatable starshade concepts. We also collected information including an analysis of the JPL starshade concept extrapolated to the 100 m scale, we refined the optical tolerance analysis, and we formed a collaboration with the MIT-NASA Ames group developing a robotic assembly system with voxels (small unit cells). We completed a Kepner-Tregoe analysis of the current concepts and conclude conclude that none of the concepts yet meet all requirements, but there are three main possibilities: an improved deployable design, an inflatable design, and a voxel design with robots. Kepner-Tregoe is a commercial enterprise and their methodology is widely applied in aerospace engineering. See https://kepner-tregoe.com/.

To summarize: We over-delivered on our technical approach and work plan.
1) We wrote peer reviewed publications to define the optical/mechanical requirements of the HOEE system.
2) We surveyed a range of mechanical configurations.
3) We conducted community challenges that resulted in over 70 proposed solutions.

4) We evaluated the results of the community challenges and our own work, followed by a Kepner-Tregoe analysis, and selected three potential candidates: improved deployable concept, inflatable concept, and cellular construction concept ("voxels") assembled by small robots.
5) We started scale model testing for the inflatable candidate.
6) We built a powerful team and workplan to advance towards a fully detailed starshade design that can meet mission requirements, and wrote a proposal for a phase II NIAC study.

2 Introduction, Unexplored Concept

For the NIAC Phase I, we proposed to solve the main technical challenge of building an ultra-light starshade for the first hybrid exoplanet observatory,[3,7] combining a 100 m diameter starshade in space with a telescope on the ground. The challenge is primarily mechanical: a 100 m object in space is hard to imagine, hard to test, hard to deploy or construct, and hard to move around in space. We set a target of 1000 kg for the starshade itself, far lower than extrapolations of existing designs. The reason is that space mission costs are roughly proportional to mass; to make the starshade competitive, it must be affordable. We argued that it must be possible given available materials, but only if new concepts could be found.

We proposed the idea in 2000[3] but it was not feasible then. The Hybrid Observatory for Earth-like Exoplanets (HOEE) would convert the largest ground-based telescopes now under construction (GMT, Giant Magellan Telescope,[4] TMT, Thirty Meter Telescope,[9] or E-ELT, (European) Extremely Large Telescope[1]) into the most powerful planet finders yet designed. No other proposed equipment can match the angular resolution (image sharpness), sensitivity (ability to see faint objects in a given time), or contrast (ability to see faint planets near bright stars). The large telescope is needed because Earth-like planets are extremely faint. The starshade is needed to block the glare of the host stars; the sun is 10 billion times brighter than the Earth at visible wavelengths. A starshade in an astro-stationary orbit would temporarily match position and velocity perpendicular to the line of sight with the telescope (which is moving due to the spin of the Earth), and cast a dark shadow of the star, without blocking the light of its planets. Active propulsion would maintain alignment during the observation. Adaptive optics (AO) in the telescope would compensate for atmospheric distortion of the incoming images,[6,11] by focusing the telescope on a laser beacon at the center of the starshade. This AO technology is already developed for the MagAO-X instrument for the Magellan 6.5 m telescope[2] and can be scaled up for larger telescopes.

The use of an extremely large ground telescope is a breakthrough innovation for HOEE, and will be available without major NASA effort, funded by Europe (for the E-ELT) or by the NSF with the TMT and GMT partners. The telescopes are so large that they form a sharp image of the starshade and its petals. Stray light from the starshade itself can be blocked, and will not look like an exoplanet. Its tolerances are 100 times looser than those that drove the design choice for the HabEx (Habitable Exoplanet Imaging Mission,[5] a 4 m space telescope with a starshade).

3 Relevance to Roadmap

The Habitable Worlds Observatory (HWO) was endorsed by the National Academy's 2020 Decadal Survey as a general-purpose telescope capable of observing Earth-like planets orbiting sun-like stars. However, the HOEE would provide capabilities far beyond those of the HWO. With an aperture 6.5 times as large as the HWO, the ELT provides exquisite angular resolution and sensitivity.

The angular resolution can clearly separate images of planets from their stars and from the circumstellar dust clouds that accompany them. The sensitivity means that faint objects can be observed quickly; an Earth could be seen in an exposure time of 1 minute, and its spectrum could be obtained in an hour, revealing the presence of oxygen and water. The superior angular resolution guarantees unambiguous detections and improved orbit parameters for the planets.

As possibly the first science-driven mission demanding ultralight structures and probably in-space assembly or manufacturing, HOEE will be a pathfinder for other low-mass space structure missions. HOEE is propelled to prominence by the intrinsic importance of the search for life elsewhere. It therefore pulls technology to an area that would not be seriously explored without the scientific demand.

Other proposed starshade missions (Exo-S, Starshade Rendezvous, HabEx, and now possibly HWO with servicing) would benefit from all of the technical innovation sought here. These have all been designed for relatively small space telescopes, ranging from 1 to 4 m in diameter. While the existing designs are constructable, launchable, and affordable, their scientific yield is limited by fuel consumption for maneuvering between targets. Their scientific value would be greatly improved by lower mass designs. Space-based very long baseline interferometry (VLBI) or a space extension of the Event Horizon Telescope would also benefit from large low mass space hardware. Lower precision structures like the sunshades for the HWO mission and proposed solar observatories would also benefit from the possibility of ultralight structures.

4 Team Members and Contributions

PI John Mather at GSFC conceived the mission and leads the search for solutions. Jonathan Arenberg (Northrop Grumman Space Systems) developed a concept for an inflatable space telescope and showed how to manage micrometeoroid punctures. Matt Greenhouse (GSFC) evaluated GrabCad.com concepts, along with John Grunsfeld (Endless Frontier Associates) and Rudranarayan Mukherjee (JPL). Eliad Peretz (GSFC) joined the study after selection. Peretz and Alejandro Rivera (GSFC) refined the mechanical design requirements for the GrabCad.com and SPS (Society of Physics Students) challenges, and developed an inflatable concept. Ahmed Soliman (JPL and CalTech) joined Stuart Shaklan (JPL) for the optical tolerances. Manan Arya (Stanford) joined the team and a student (Arantzazu Ramos del Valle) performed a mechanical optimization. Neil Gershenfeld (MIT) and Christine Gregg (NASA Ames) joined the team and contributed concepts for robotic assembly of volume elements (voxels). Anthony Harness found alternate employment. James Stratford of Universal Science (UK) fabricated test units for the inflatable starshade concept.

5 Accomplishments

The main determinants of successful designs are overall shape and materials choices. The shape parameters like thickness to length ratio determine mechanical mode resonant frequencies and deflection under load. The materials choice has effect through the specific stiffness (ratio of Young's modulus to density) and specific strength (ratio of yield strength to density). Mechanical resonant frequencies scale in proportion to the square root of the specific stiffness, and inversely with overall size. Deflections under acceleration scale inversely with specific stiffness. Neither of these scales with total mass, showing that clever design might achieve our objectives. Dimensional analysis shows that scale models can be tested at the same strain levels if the acceleration is inversely proportional to the scale size, or if the specific stiffness is proportional to the scale size. If we wish to gain experience in our 1 g environment, then we can use Mylar with a specific stiffness of $1.7 \times 10^6 \mathrm{m}^2/\mathrm{s}^2$ to emulate a carbon fiber structure 66 times larger, with a specific stiffness of $113 \times 10^6 \mathrm{m}^2/\mathrm{s}^2$.

We proposed to find at least one mechanical design concept for an orbiting starshade with a mass of 1000 kg (just for the deployed starshade itself), that could potentially meet all requirements. Given that prior concepts were very far from this target we planned to do our own conceptual development, and to sponsor a student competition through the Society of Physics Students (SPS). Following initial work we proposed to do a Kepner-Tregoe analysis of alternatives, to determine where to concentrate our efforts in Phase II.

1. We completed the definition of the mechanical requirements, including shape, stiffness, and strength.

2. We expanded our initial plan for student studies and professional analysis to include a GrabCad.com design competition via the NASA Tournament Lab in STMD's Prizes, Challenges, and Crowdsourcing program `https://spark.nasa.gov/nasa/crowdsourcing-contenders-2024_359/overview`. The GrabCad.com program can be seen at this link: `https://grabcad.com/challenges/nasa-challenge-ultralight-starshade-structural-design` This link includes the mechanical requirements levied on the contestants, shows images and descriptions of the 59 entries, and names the 9 winners.

3. From our internal analysis we determined that an inflatable structure is well worth exploring. It has the advantages that a) launch packaging can be very compact, b) the system can be rigidized after launch without the need for continuous inflation, and c) nearly optimal mechanical structures can be imagined and constructed.

4. In our proposal we claimed that the optical tolerances are much looser for the orbiting starshade than for smaller starshades with smaller telescopes. We verified this using the online SISTER simulation tool, and results are given in the appendix.

5. We designed a full scale inflatable starshade, 100 m in diameter, estimated its mass (1600 kg), and initiated studies of small inflatable test items.

6. We analyzed the existing deployable designs, to see if they could possibly be reduced in mass to our target requirement. While we have not yet achieved this, we believe it is possible, and through Manan Arya we found one optimized design concept that has half the mass of the prior design.

7. We also discovered that there is an existing program at NASA/Ames and MIT to assemble large structures using small robots and voxels (volume elements). Initial results are promising and described below.

6 Design Requirements

These were set before we initiated the GrabCad.com and student competitions. None of the competitors gave detailed responses but the winner of the student competition (a team at the University of Notre Dame) came closest, with a proper engineering approach and a tabulation of requirements. See illustrations below.

6.1 Environment

Must survive in operational environment: High Earth Orbit, 12,000 km perigee, 189,000 km apogee, including radiation, micrometeoroids, and temperatures.

6.2 Mechanical Requirements and Desires

The in-flight structure must be stiff and must recover quickly from changes, because rocket thrust is required about once per minute to hold the starshade in alignment between the star and the telescope. We also analyzed the required angles relative to the Sun and the line of sight, to enable a significant observing program. The requirements are as follows:

6.2.1 Strength

The system must tolerate up to 0.03 g's of acceleration in any direction without damage. This is particularly important since large structures with thin skins can easily buckle or crumple, but if they are not damaged, they might still be used. The acceleration level could be reduced to 0.003 g's if we could prove that the rocket jets are invisible to the telescope, but that is outside the scope of this work.

6.2.2 Mass

We set a target mass of 1000 kg, but this is not an absolute requirement. Mission cost is thought to be proportional to mass, since propulsion is a key requirement.

6.2.3 Impulse Recovery

The system must either maintain its shape within tolerance during rocket thrust, or recover it within 10 seconds after the thrust is ended.

6.2.4 Shadow Shape

The shape of the star shadow is given by a numerical optimization code. It resembles a pointy sunflower with at least 24 petals. The center is 50 m in diameter and is opaque. The petals taper gradually to sharp points with a formula simulating a Gaussian taper, but faster. Each petal is 25 m long.

6.2.5 Shadow Shape Tolerance

Many types of shape errors are evaluated, and we confirmed that the requirements are much looser than for prior starshade designs. We are solving the hardest problem first, and assuming that future work can keep the shape errors within limits.

6.2.6 Edges

The edges of the starshade have to be sharp, otherwise sunlight glinting off them will overwhelm the observations. The JPL deployable designs required razor sharp metal edges. But the large telescope on the ground has an internal coronagraph to block the light from the starshade, including glint from the edges. The ELT is so large that it can resolve the edge glints and separate them from exoplanet images very well. For now we are assuming that ordinary plastic edges will be sharp enough, subject to further analysis.

6.2.7 Edge on to the Sun

The nominal orientation of the starshade plane is edge-on to the Sun, to maximize the range of observing angles available. However, the plane must be tilted somewhat so that any starshade structure on the underside (facing Earth) is not illuminated by the Sun.

6.2.8 Tilt relative to the Line of Sight

We wish for a range of $\pm 30\,\mathrm{deg}$ tilt relative to the nominal case, where the starshade plane is perpendicular to the line of sight. Simulations show that the shadow is still dark enough with this range of tilt. However, there is now a new requirement, that none of the structure of the starshade can project over the edge of the shadow. This means that even the part of the structure that is illuminated by the Sun is still invisible to the telescope.

6.2.9 Leakage

Sunlight and starlight leaking through holes, micrometeoroid punctures, seams, and gaps in the starshade must be very faint, otherwise the starshade will be much brighter than the star and its planets. It seems likely that at least two opaque layers are required, with a blackened region between them.

6.2.10 Earth reflectance

The Earth is very bright as seen from the starshade, and any radiation coming back from the starshade will resemble the light of an exoplanet. Various design possibilities are available, ranging from specular (oriented to reflect the Earthshine away) to black.

6.2.11 Deployment

There must be a concept for in-space deployment, assembly, or construction.

6.2.12 Testing

We need a concept for testing on the ground, or a reason why it is unnecessary.

6.2.13 Central Tube

We need a reserved volume for the spacecraft bus, including fuel tanks, jets, refueling equipment, communications, etc. We require a 2 m diameter clear tube at the center.

7 Progress on Phase I objectives

7.1 Optical Tolerances

Team member Shaklan met a new member of the JPL technical staff (Ahmed Mohamed Soliman) and asked him to do a complete tolerance analysis for the starshade shape errors. Key results verify our prior claims that the starshade shape tolerance is at least 10 x looser (100-1000 X improved contrast) than for smaller starshades, and that the starshade alignment can be up to 1.4 m off direct center without exceeding requirements (contrast = $5{\times}10^{-12}$). Results are summarized in Table 1.

The tolerance analysis of the 99 m starshade has been performed assuming the Extremely Large Telescope (ELT). The starshade consists of 48 petals and 24 segments along each edge of

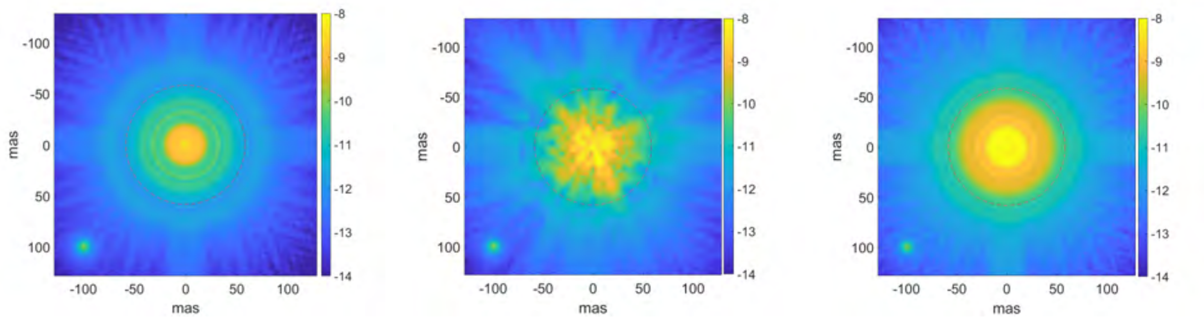


Fig 2 Left: The unperturbed nominal intensity. Middle: Randomly perturbed intensity (1σ petal radial displacement amplitude = 100 mm). Right: Globally perturbed intensity (fixed petal displacement amplitude = 100 mm). Figures 13 and 14 show more details about the contrast and expected quadratic relation for both cases. A 10^{-10} planet is shown at in the lower left corner of the images. The dashed circle shows the IWA of 58 mas.

the petal. We first computed the nominal unperturbed field over 690-700 nm, as shown in Figure 2. The resulting contrast is 2×10^{-12} at the Inner Working Angle (IWA) = 58 mas. We computed the unperturbed contrast to be 2-3$\times10^{-12}$ over the 400-1000 nm, as shown in appendix A.1. We perturbed the starshade to see how the leaked starlight changes from nominal. We tested several perturbations related to petal position, petal shape, petal clocking, segment position, formation flying offset errors, and proportional petal errors in width and length. We looked at global perturbations (common to all petals and/or all petal parts) and random perturbations (different on each petal and/or petal part). Detailed perturbation definitions are provided in appendix A.1. The sensitivity coefficient for starlight leakage at the IWA is given by $C = a * pert^2$. Coefficient 'a' of all perturbations are listed in table 2 of the appendix. Table 1 presents the computed perturbations resulting in a change of contrast of 5×10^{-12} at the IWA.. The contrast-perturbation plots shown in the appendix produce the expected quadratic relation. The results, shown on tables 1 and 2, suggest that these errors are very well forgiven and our design is very robust. These sensitives remain the same in the presence of the atmosphere as long as we have an effective adaptive optics system. Additionally, the contrast for the HOEE 99 m starshade was 100-1000x contrast reduced compared to the 60 m starshade for the Habitable World Observatory (HWO), with the same perturbation proportional sizes. Further details and a comparison to a proposed HWO starshade are discussed in the appendix A.2.

Perturbation list	Perturbation type	Amplitude
Petal displacement	Radial/Global	46 mm (fixed)
	Radial/Random	66 mm (1σ)
Segment displacement	Vertical direction	280 um
Petal clocking	Random	4.2 mradians (1σ)
Formation offset error (RA and DEC)		shift=1.4 m

Table 1 The allowable perturbations resulting in a contrast increase of 5×10^{-12} at IWA=58 mas, over 690-700 nm band. The global perturbation is based on a fixed amplitude. The random perturbation is based on the standard deviation displacement. The full coefficients for all perturbations are listed in table 2.

7.2 NASA Tournament - GrabCad.com

Working with Kevin Kempton at the NASA Tournaments office, we defined a challenge for the GrabCAD.com online design community. We were most interested in radical concepts, such as inflatable designs and tensegrity structures. "Tensegrity" is a term coined by Buckminster Fuller in the 1960's, and refers to systems in which cables are in pure tension, and other elements are in pure compression. We received 59 submissions and granted small prizes to 9 (funded by the Tournaments office). These submissions are all visible with a free account on GrabCad.com; sign in and search for "starshade". None of the designs showed stiffness or strength calculations, but some did show plausible mass estimates.

We provided a technical library, as follows:

HabEx Final report: `https://www.jpl.nasa.gov/habex/pdf/HabEx-Final-Report-Public-Release-LINKED-0924.pdf`

NIAC summary: `https://www.nasa.gov/directorates/spacetech/niac/2022/Hybrid_Observatory_for_Earth_like_Exoplanets/`

Starshade tutorial – Doug Lisman: `https://www.jpl.nasa.gov/habex/documents/Aug2016/Lisman-Starshade.pdf`

Starshade tutorial – Steve Warwick: `https://www.jpl.nasa.gov/habex/documents/Aug2016/Warwick-NG-design-briefing-to-HabExSTDT.pptx`

In-space assembly strategy: `https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf`

Falcon Users Guide: `https://www.spacex.com/media/falcon-users-guide-2021-09.pdf`

ExEP web site `https://exoplanets.nasa.gov/exep/starshadedocuments`
`https://exoplanets.nasa.gov/exep/technology/starshade/`
`ExoplanetStrategyreporthttps://www.nap.edu/read/25187`

SPIE JATIS special issue: `https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-7/issue-02/021201/Special-Section-on-Starshades-Overview-and-Dialogue/10.1117/1.JATIS.7.2.021201.full?SSO=1`

ORCAS report on adaptive optics:`https://asd.gsfc.nasa.gov/orcas/docs/ORCAS_AS3_Study_HQ_Report_Origin_Public_Version.pdf`

Many books and papers are published on metamaterials materials. For example this article by Roderic Lakes, at U Wisc: `http://silver.neep.wisc.edu/~lakes/home.html`, and his book "Composites and Metamaterials, July (2020)".

`https://ui.adsabs.harvard.edu/` is an interface to articles relevant to astrophysics and includes SPIE journals.

Abner Gomez was the first place winner and his concept is shown in Figure 3.

The second place winner was Joe.Taylor-25 with the LDAS concept, illustrated in Figure 4.

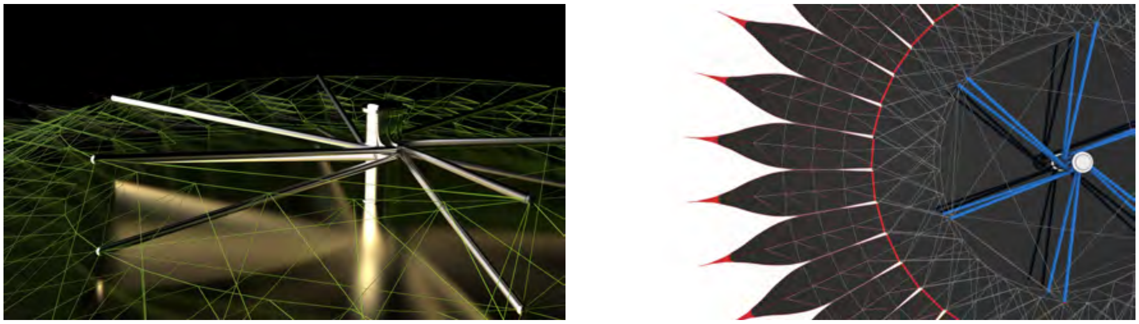


Fig 3 Left: Side view of Omega Project by Abner Gomez. Right: top view

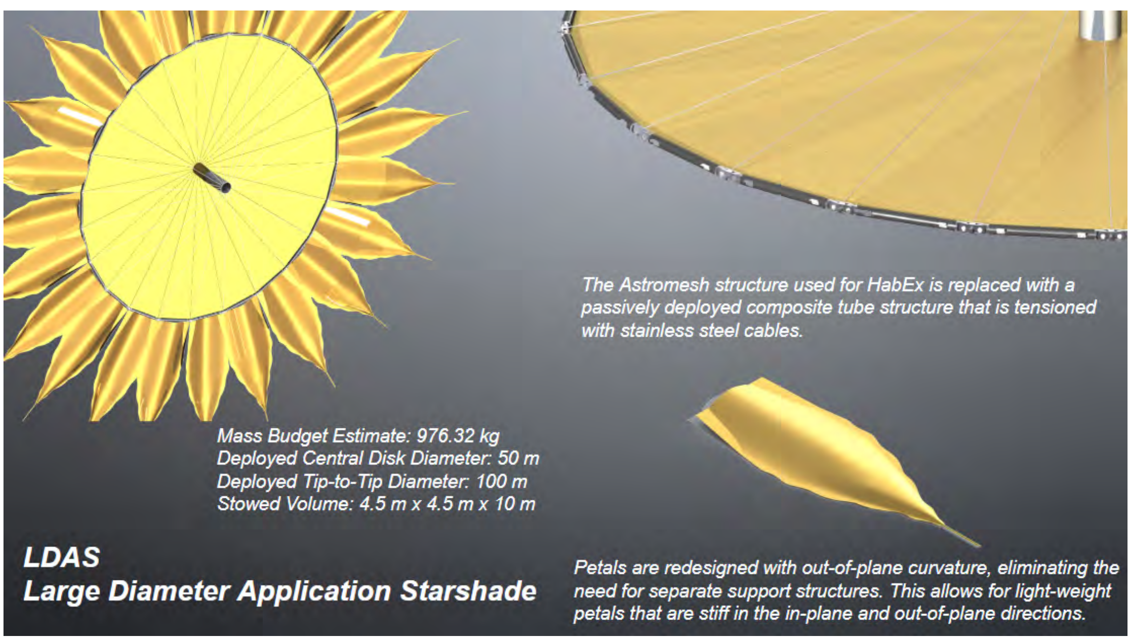


Fig 4 LDAS - Ultralight Starshade Design Concept by joe.taylor-25

Fig 5 Breana Patz concept

7.3 Student Challenge at SPS

As proposed we issued a grant to the Society of Physics Students, an activity of the American Institute of Physics. Responses to our initial announcements in 2022 to a mailing list of college and university physics and engineering departments were disappointing, but one brilliant undergraduate (Breana Patz) at Michigan Technical University submitted an excellent design concept, illustrated in Figure 5.

We therefore requested a no-cost extension of the NIAC grant and extended the SPS grant to a second year. This time in 2023 the SPS actively solicited individual faculty members to sponsor the student competitions, and organized a series of online seminars to encourage them.

We issued instructions requiring hand calculations of strength and stiffness, so that the students would learn some engineering instead of learning how to turn the crank on a pre-written design tool.

The result was a list of 7 teams: Slim Shady (Roanoke College), Zeus Starshade Project (New York University), ULL SPS GIRS Design (University of Louisiana at Lafayette), LUStem (Lamar University), IrishSat (University of Notre Dame), Rainbow Road (Massachusetts College of Liberal Arts), and Starshade Racers (Murray State University). These teams were volunteers and most found that they did not have time for serious calculation, in competition with their classroom assignments.

There were many clever suggestions. For instance, one team suggested that deployable rigid tubes could be inflated like a sausage being extruded, and that they could be filled with foam to

Fig 6 IrishSat concept 2 meter model

rigidize them and prevent buckling.

The most promising student design is the IrishSat. The students followed an excellent organized approach, documented their work, showed their hand calculations, and sent many photos of their model. Examples are shown in figures 6, 7, and 8.

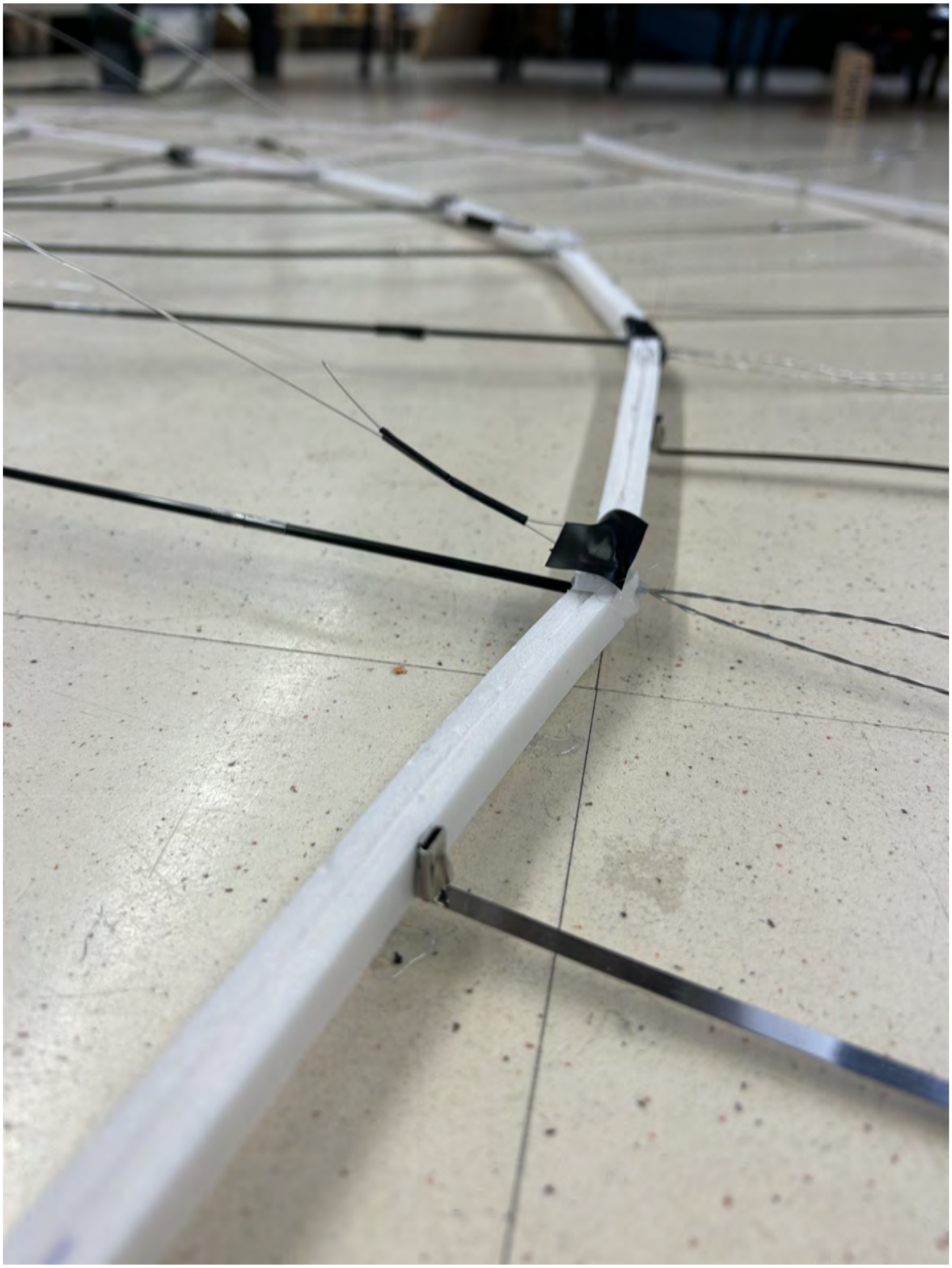


Fig 7 IrishSat concept detail

Fig 8 Irish Sat detail

7.4 Deployable designs

Dr. Manan Arya, a former starshade designer from JPL, now teaching at Stanford, found a masters student (Arantzazu Ramos del Valle) to analyze and optimize the JPL starshade design, extrapolated to our 100 m scale. The result was that the starshade mass was 3000 kg (not counting the spacecraft bus), but this was still an improvement over the JPL Team-X design that we obtained in 2019. The first mode frequency is 0.5 Hz and the estimated wet mass including the propulsion system is 20,421 kg. The concept is illustrated in Fig. 9. Numerical results are tabulated in Fig. 10.

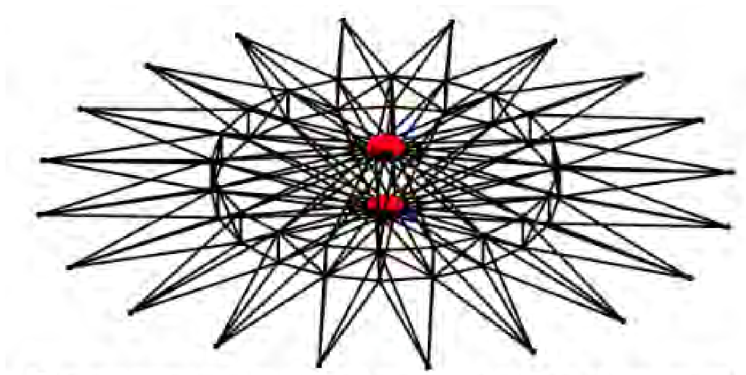


Fig 9 Simplified Stanford concept for optimization

We consider this as a benchmark for comparison with our other concepts, as it is calculated and optimized with a simplified finite element model. Their study also demonstrates that the total mission mass is of order 7 times the mass of the starshade itself, confirming the importance of reducing that mass.

7.5 Inflatable Structures - Rivera and Peretz

Dr. Peretz provided the starshade shape, optical and mechanical tolerance analysis,[8] based on the Kepner-Tregoe analysis conducted by Mather and Peretz. Rivera developed a comprehensive review of deployment techniques for ultralight structures. He concluded that an inflatable design could meet requirements, and developed analytic calculations of strength and stiffness for a number of alternatives. The jointly developed concept uses an inflated torus to stretch out the center 50 m diameter section, and act as a base for attaching the 25 m petals. The design includes cabling and additional elements to ensure shape precision and static/dynamic stability.

We consider that this approach is technically credible. It has potential advantages of small packaged volume and low cost. Inflatable systems have been used on multiple missions since the late 1950s, though none at this scale and precision. We found a very thorough review article[10] from 2014 about inflatable deployable booms, and used its results in our design. It might be possible to inflate with helium to help with gravity compensation in ground deployment tests. Current mass estimates for our concept are in the 1000 - 1500 kg range. We received numerous suggestions in our competitions about designs of tubes and petals, but none were given in detail. The top-level design seems close to meeting the mass requirements.

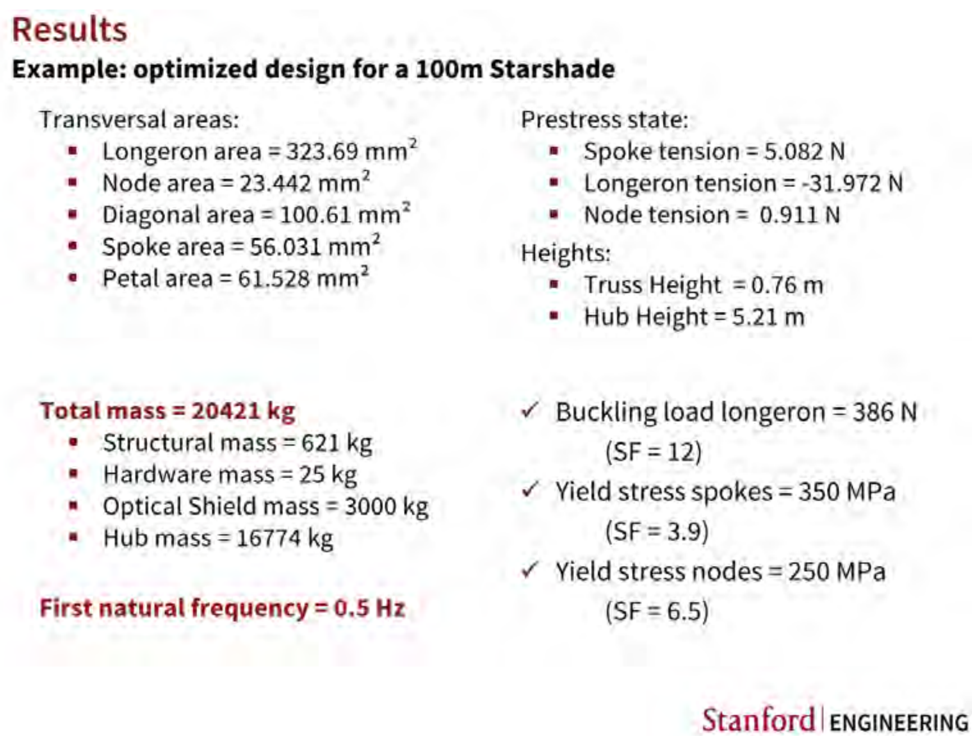


Fig 10 Stanford analysis results

Rivera plans to use this work as the basis of a PhD thesis at the University of Maryland, under Prof. David Akin. However this has been deferred due to his urgent main job as chief deployment engineer for NASA's next great telescope, the Nancy Grace Roman Space Telescope (Roman). His work on Roman is expected to taper off by mid 2024.

There are design choices about whether to use cables to stabilize the torus (like a bicycle wheel and the prior deployed designs) or to use stretched membranes for the same purpose, since they are already needed for opacity.

Given the micrometeoroid flux, etc, it is challenging to maintain significant pressures in large gas inflated objects, but there are numerous ways to rigidize a plastic surface after deployment, including chemical (e.g. through exposure to UV sunlight), or thermal (allowing a material to cool below its glass transition temperature).

No deployable structure of this size or tolerance has been flown, so we estimate the TRL (Technical Readiness Level) is 2.

In the first phase of our project, we: a) Developed a rigorous analytical model capable of computing the total mass, stiffness, required inflation pressures, static and dynamic stability loads, and stresses on all critical structural components, as well as the starshade's fundamental frequency, b) Developed an origami-based folding strategy that shows that the entire starshade can be easily accommodated inside the Falcon Heavy Fairing, c) Developed a deployment strategy that starts from a fully stowed position inside the LV (launch vehicle). The starshade is expanded in a controlled manner, then inflated, and finally, the cables are preloaded to ensure a stiff deployed structure. The deployment phase of an inflatable mission is considered to be the most complex and critical one. d) Outlined a design for a an inflation system, which is based on the one that achieved success during the Inflatable Antenna Experiment (IAE). The proposed design shares components with the

Attitude Control system. e) Analyzed rigidization materials and selected sub-Tg resins for their many benefits, including reversibility and ground testability of the starshade. These resins become rigid below their glass transition temperature Tg, and can be customized to meet specific needs. The starshade has a long shelf life, and unlimited pre-deployment lifespan. The starshade can be kept warm by fully facing the Sun during deployment, and then allowed to cool. f) Identified a vendor for the construction of our 1:50 and 1:100 scale starshade mockups. These mockups will be used to perform packaging, deployment controllability, deployment dynamics, and inflation system tests and studies in the NIAC Phase II. g) Acquired samples of materials and located fabrication facilities at Goddard. h) Conducted a peer review of our concept, with L'Garde engineers who confirmed that our proposed strategies and methods are in line with their own. L'Garde Engineering is the leading inflatable structures and technology company in the United States. They have been involved in the development of numerous space-based inflatable technologies, including inflatable habitats, antennas, and solar sails. Dr. Peretz and Alejandro Rivera will lead this effort.

Further analysis is still required. Key questions still open are: how to avoid or recover from buckling and crumpling in thin shells and tubes? Should they be filled with foam? Should they be re-inflated temporarily to withstand the acceleration during observation? (It seems impossible to keep them inflated, given the flux of micrometeoroids.) How should we control the temperature during deployment, and after, since we are counting on low temperature to maintain rigidity? How should the inflatable system be constrained by stiff structures so that it meets the shape tolerances? Also, would it be possible to deploy the system here on Earth for tests, and how would we do g-negation? All of these will be important to answer before the 6 month decision point.

Through a wide telephone campaign, Dr. Eliad Peretz discovered that James Stratford at Universal Science (UK) Ltd already has the capability to design and build an inflatable sunshade, with sizes up to 10 m available with current technology. Aside from learning from trial and error, there is a strategy to emulate living structures like plant leaves with their ribs and veins. Stratford has already made samples of inflatable systems at the 1 m scale. NASA has also acquired (with other funds) the necessary equipment to bond starshade layers together and make inflatable structures such as sunshades and starshades. Peretz has begun testing sample devices at GSFC.

Peretz also worked with members of the Heliophysics Division at GSFC, who are designing a deployable sunshade. An example test device is shown in Fig. 11.

7.6 Voxel Robots

In the course of our work we found that Neil Gershenfeld, director of MIT's Center for Bits and Atoms, was already developing a voxel-robot deployment process, in collaboration with NASA Ames (Christine Gregg et al.)

`https://news.mit.edu/2022/assembler-robots-structures-voxels-1122`. Voxels are small unit cells, that can be assembled by small robots. In this case laboratory demonstrations have been made at the 10 cm cell scale, though there is no intrinsic scale. In principle any solid object can be subdivided into volume elements that can be assembled with tiny robots. Therefore, this concept is of great interest for our starshade work. It is too soon to promise that this approach can meet the strength and stiffness requirements, but it seems very likely that it can meet shape and deployment requirements. Given that there are robots everywhere, the system is robust against individual failures. The robots could be used to adjust the shapes of the petals after launch, or to provide active damping of vibrations.

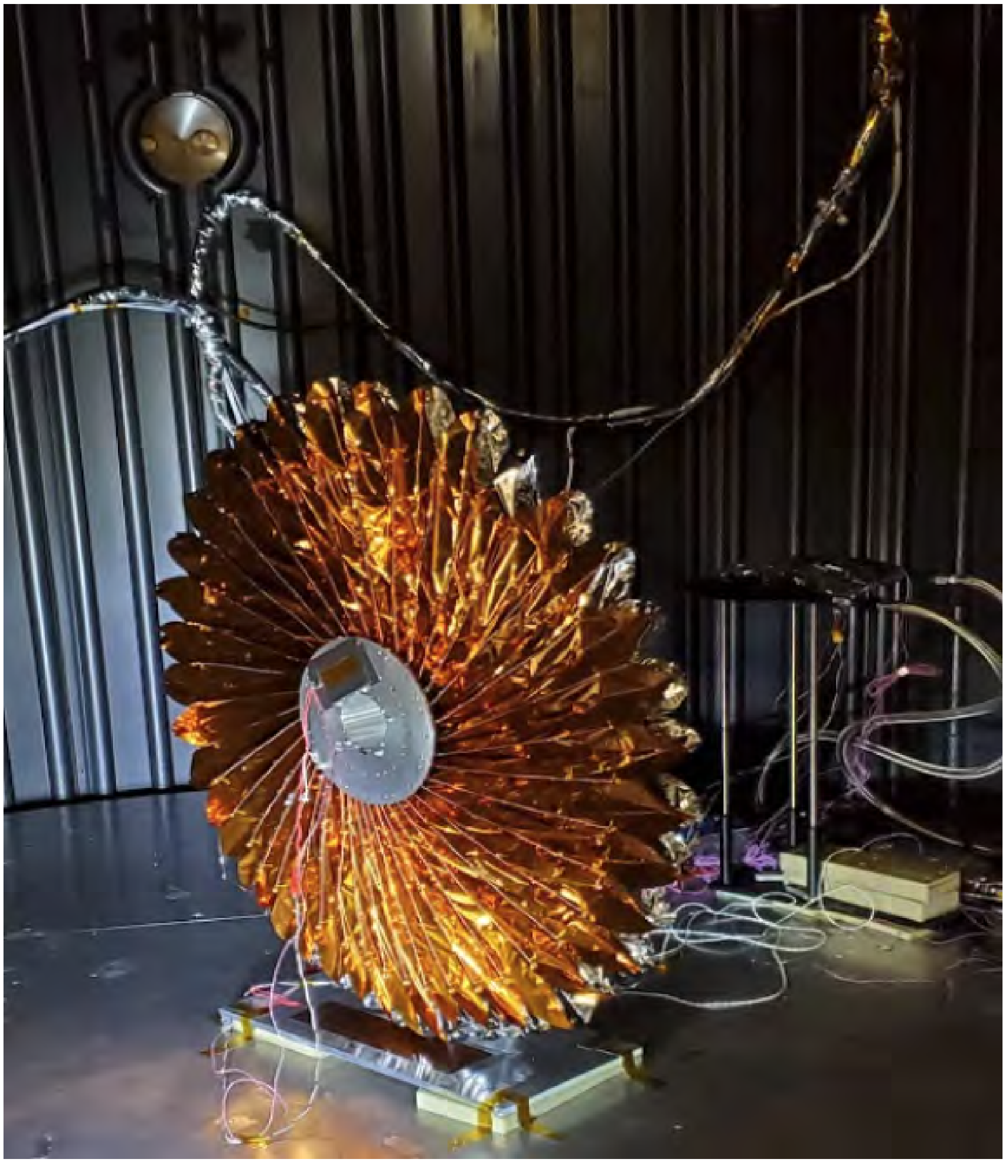


Fig 11 GSFC Sunshade deployment test article

8 Process - Kepner-Tregoe Analysis

The Kepner-Tregoe analysis we proposed to do calls for a clear separation between hard requirements (Musts) and others. For our MUST list we wrote: 1. Mass is most important; the stated target is 1000 kg for the starshade itself. For the KT analysis, we required 1500 kg. Reason: mission cost including propulsion is proportional to mass. 2. Maintain shape and shadow, following acceleration [mean 0.003g, 0.03g peak, 10% duty cycle], thermal changes [sun and dark sides], etc., including sunlight and earthshine reflections. Reason: to provide required optical performance, including maintain shape up to 30 degree tilts. 3. Needs to survive in operational environment [HEO, 12,000 km perigee, 189,000 km apogee] (Radiation, micrometeoroids, temperature; shadow must be opaque including leakage and reflection from starlight and sunlight.) For now all of these are a little fuzzy in the sense that we do not have complete solutions so we must estimate which ones could be successful with further effort. This becomes part of a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threarts).

9 Next Steps

We used the K-T analysis to select the winners of our design competitions at GrabCad and university student teams. We also reviewed the concepts at a higher level, and concluded that we have three options for further development:

9.1 Deployable

A deployable system, based on prior work. We have already found a 3000 kg conceptual approach, much lower than the prior extrapolation of 6809 kg from the Team-X study at JPL. There were many clever suggestions from the GrabCad designers. Lower density materials (e.g. through perforations, hierarchical structures, or cellular construction) can preserve the specific strength and stiffness while reducing mass. Beryllium has been ignored in the past but has much higher specific strength and stiffness than other aerospace materials, and might solve our problems.

9.2 Rigidized Inflatable

A rigidized inflatable system could have many advantages. It could have very high packaging density and low mass. A potentially small mass and volume and relative simplicity could enable a flight deployment test program. If rigidized with sub Tg resins, it could have a long shelf life and could be inflated numerous times for tests. Initial mass estimates (1600 kg today) show that it could meet the requirements.

9.3 Voxel Cellular

The voxel system with many small assembly robots has a TRL of 4 at small scales, but has never been applied to something so large, or in space, or with our stiffness and strength requirements. However, it has significant advantages too. As it is assembled in space with small robots, it can build on small-scale laboratory work, and no large general purpose robots or giant manipulator arms are required.

We will propose a trade study to the NIAC phase II in 2024. After 6 months of serious engineering we will downselect to one of the three options, and develop it sufficiently to be the basis of a flight mission.

10 Recent Team Publications of NIAC-related work

Including pioneering voxel work:

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[Cameron:22] Cameron, Christopher G., Zach Fredin, and Neil Gershenfeld. "Discrete assembly of unmanned aerial systems." In 2022 International Conference on Unmanned Aircraft Systems (ICUAS), pp. 339-344. IEEE, 2022.

[Hildebrandt:21] Sergi R. Hildebrandt, Stuart B. Shaklan, Eric J. Cady, and Margaret C. Turnbull. Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance. Journal of Astronomical Telescopes, Instruments, and Systems, 7(2):1 – 48, 2021.

[Mather:19] ASTRO2020 APC White Paper – "Orbiting Starshade: Observing Exoplanets at visible wavelengths with GMT, TMT, and ELT," J. Mather et al., 2019

[Parra Rubio:23] Parra Rubio, Alfonso, Klara Mundilova, David Preiss, Erik D. Demaine, and Neil Gershenfeld. "Kirigami Corrugations: Strong, Modular, and Programmable Plate Lattices." In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 87363, p. V008T08A049. American Society of Mechanical Engineers, 2023.

[Parra Rubio:23.1] Parra Rubio, Alfonso, Dixia Fan, Benjamin Jenett, José del Águila Ferrandis, Filippos Tourlomousis, Amira Abdel-Rahman, David Preiss, Jiri Zemánek, Michael Triantafyllou, and Neil Gershenfeld. "Modular morphing lattices for large-scale underwater continuum robotic structures." Soft Robotics 10, no. 4 (2023): 724-736.

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[Peretz:21c] ORCAS - Orbiting Configurable Artifical Star Mission Architecture Proceedings of SPIE, Volume 11819, 1181905; 20 Aug 2021

[Peretz:21d] ORCAS AS3 Final Report, https://asd.gsfc.nasa.gov/orcas/docs/ORCAS_AS3_Study_HQ_Report_Origin_Public_Version.pdf

[Peretz:22] Peretz, E., Hamilton, C., Mather, J., D'Amico, S., Michaels, A., Pritchett, R., Yu, W., Wizinowich, P.; "Astrostationary orbits for hybrid space and ground-based observatories;"J.

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Appendix A: Shape Tolerancing

A.1 More analysis of the starshade tolerance

The 99 m starshade tolerancing for HOEE has been studied with the ELT and a starshade altitude of 175,000 km. Figure 12 shows the full system diagram and the resulting unperturbed contrast sensitivity over 400-1000 nm. The tolerance analysis of the starshade has been performed with electric fields at the focal plane of the telescope. The resulting fields are computed at the telescope aperture using a line-integral propagator and then at the telescope focal plane using a standard Fourier propagator. We have studied the starshade's sensitivity to different perturbations. Generally speaking, the tolerance analysis for the starshade shape error addresses the petal displacement and shape inaccuracies (Radial, Lateral, Global, and Random), segment displacement (vertical and horizontal directions), proportional petal perturbation (length and width), petal clocking (in-plane petal rotation), and formation flying offset (RA and DEC shifts). The displacement analysis includes either the radial direction (parallel to the spine of the petal) or lateral direction (perpendicular to the petal spine). In the global study, the perturbation is added equally to all petals on the starshades,while in the random study, each petal around the starshade will be perturbed individually. This refers to the radial displacement of a petal, or a shape error on one of the petal segments.

The segment perturbation displaces the optical edge segments in the plane of the starshade, both tangentially to, and orthogonal to, a petal's nominal local edge orientation. It is assumed that the terminal edge of the petals of any starshade will be made up of several optical edge segments. The proportional petal perturbation applies a proportional width and length error to each petal, specified in parts per million (ppm). The petal clocking perturbation rotates each petal in-plane about the base of the petal by some specified angle. The formation flying offset error is defined as the amount of shift it takes to increase the contrast at the IWA by 5E-12 Figure 13 shows examples of the randomly perturbed and globally perturbed starshade. Figure 14 shows the resulting expected quadratic relation of the contrast versus perturbation. The sensitivity coefficient for starlight leakage at the IWA is given by $C = a * pert^2$. We list coefficient 'a' all perturbations in table 2.

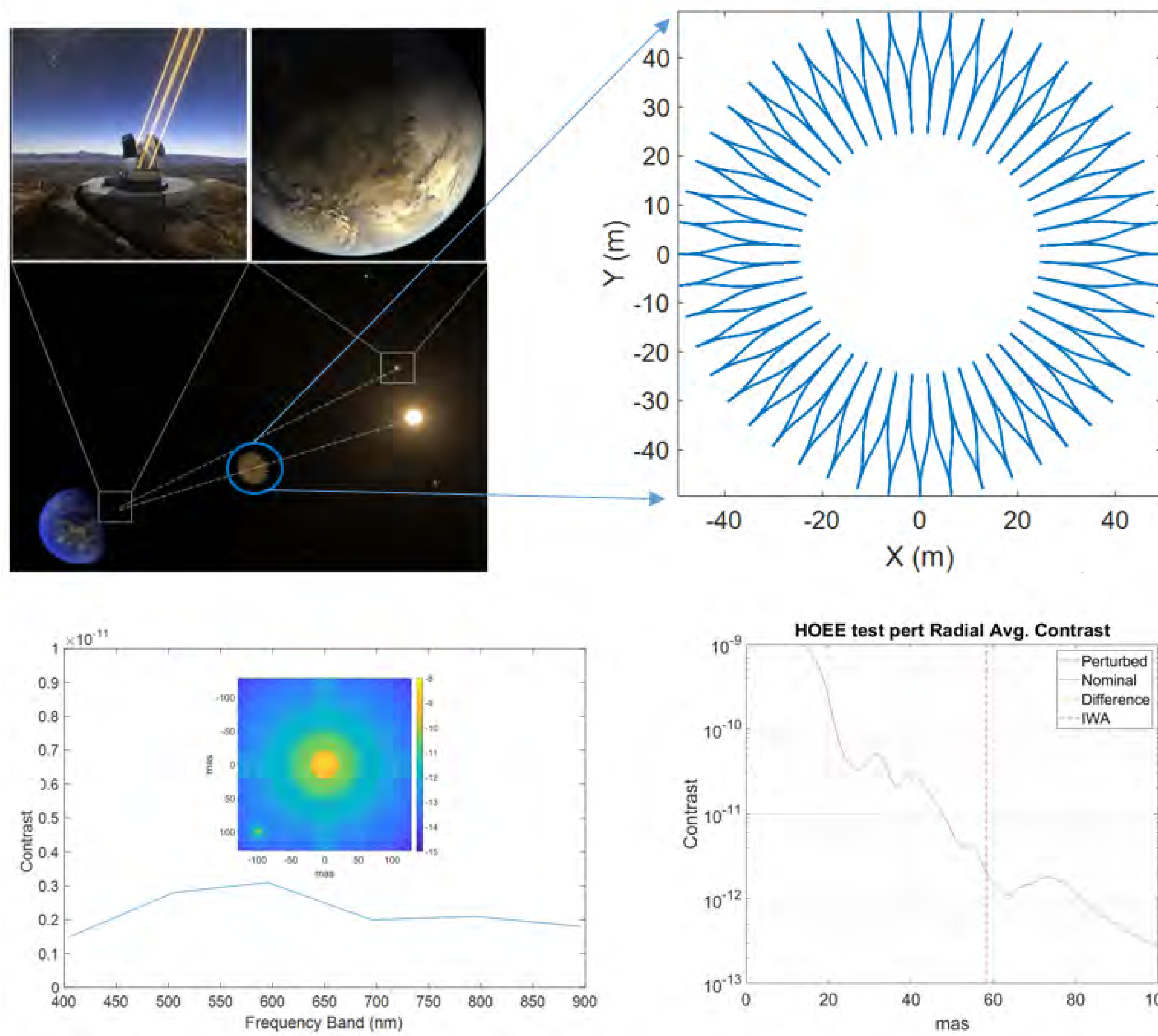

Fig 12 The 99 m starshade within the full system diagram. The computed nominal contrast without perturbations for 690-700 nm (bottom/right), and over 400-1000 nm (bottom/left), suggesting a 2-3 10^{-12} over the full spectrum.

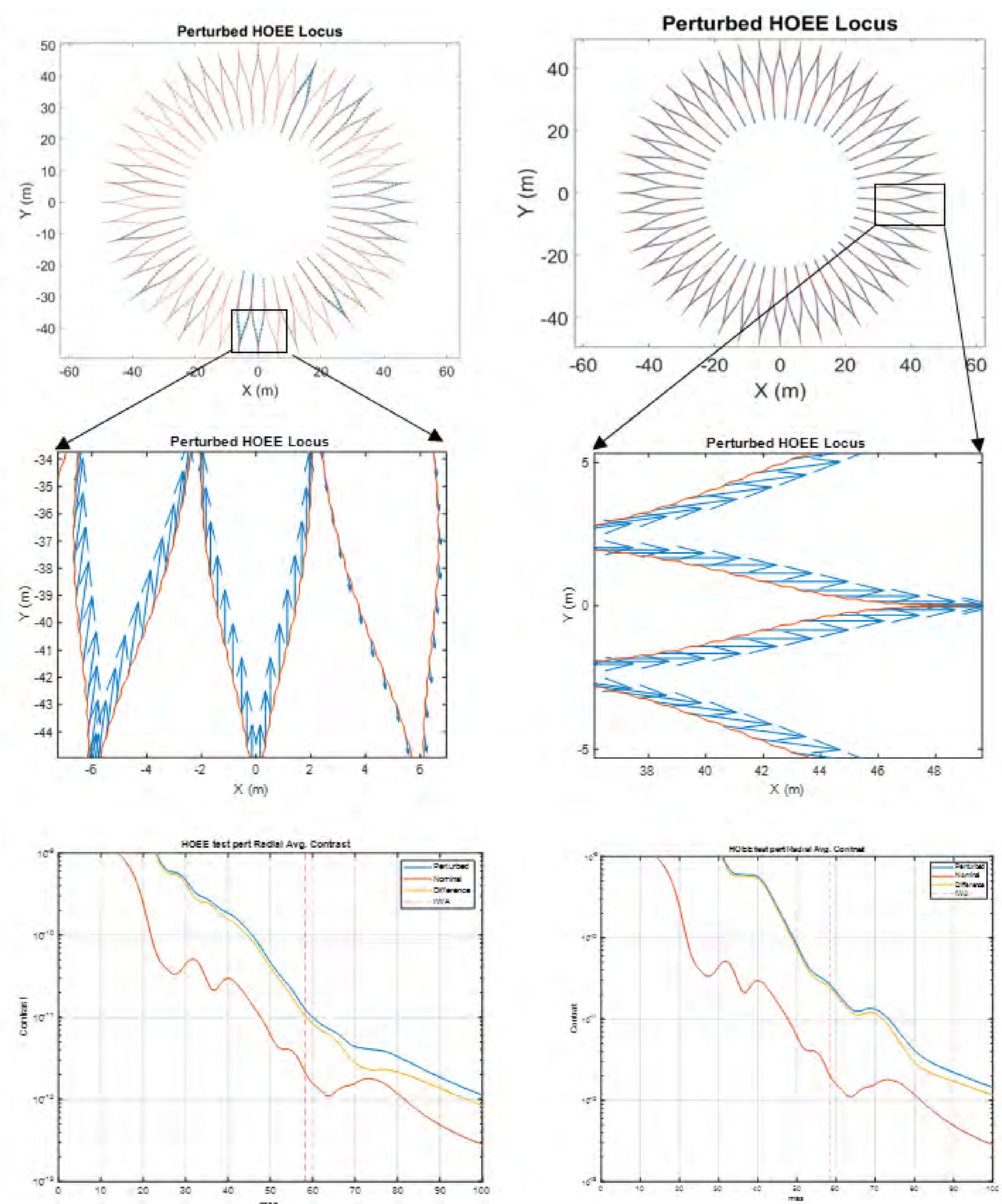

Fig 13 The 99 m starshade analysis of petal perturbation (amplitude = 100 mm). Random perturbation (left plot) versus Global perturbation (right plot).

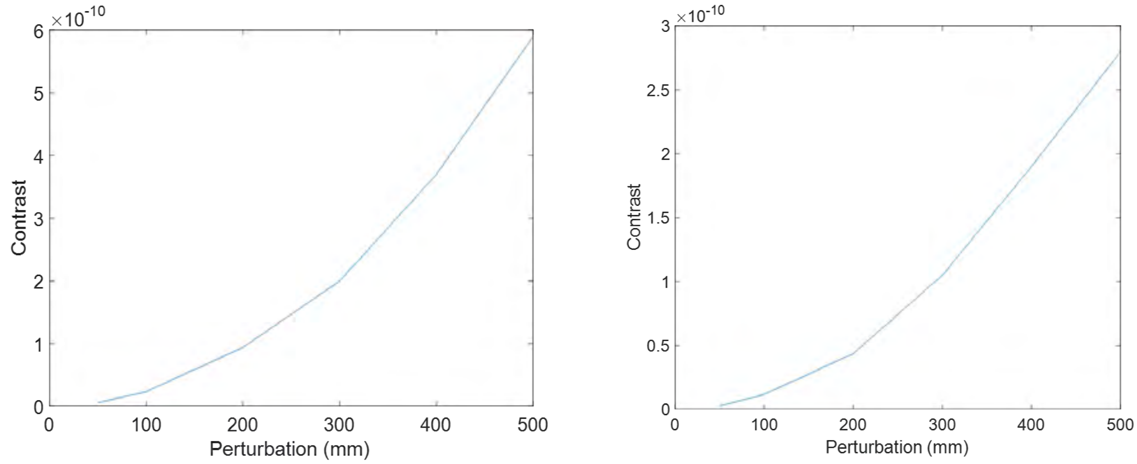

Fig 14 The contrast versus perturbation of the petal displacement (Random versus Global), showing the expected quadratic relation.

Perturbation list	Perturbation type	Sensitivity coefficient (a)
Petal displacement	Radial/Global	2.33E-09 m^{-2}
	Radial/Random	1.14E-09 m^{-2}
	lateral/Random	1.77E-07 m^{-2}
Segment displacement	Vertical direction	6.46E-05 m^{-2}
	Horizontal direction	1.52E-06 m^{-2}
Proportional petal perturbation	Width: Global	1.51E-18 ppm^{-2}
	Width: Random	4.45E-19 ppm^{-2}
	Width: Random	8.62E-21 ppm^{-2}
	Width: Random	8.35E-21 ppm^{-2}
Petal clocking	Random	2.89E-19 $uradians^{-2}$
Formation offset error (RA and DEC)		5E-12 (shift=1.4m, 400-410 nm)
Formation offset error (RA and DEC)		5E-12 (shift=1.4m, 690-700 nm)
Formation offset error (RA and DEC)		5E-12 (shift=1.2m, 790-800 nm)
Formation offset error (RA and DEC)		5E-12 (shift=0.8m, 890-900 nm)

Table 2 The 99 m starshade Analysis summary. The global perturbation is based on a fixed amplitude. The random perturbation is based on the standard deviation displacement.

A.2 HOEE versus HWO

This section compares the 60 m starshade of HWO and the 99 m starshade of HOEE. The unperturbed contrast for both starshades is shown in Figure 15. We applied a list of similar perturbations to both starshades, given the proportional size (60/99), and recorded the leaked starlight changes from nominal. In Figure 16, the perturbed contrast (yellow curves) show 2.5×10^{-11} (IWA=58 mas) and 1×10^{-8} (IWA=65 mas) for 99 m and 60 m starshades, respectively. These results suggest that the 99 m starshade for HOEE yields 100-1000X deeper contrast than the 60 m starshade for HWO, given the same perturbation combinations and proportional size.

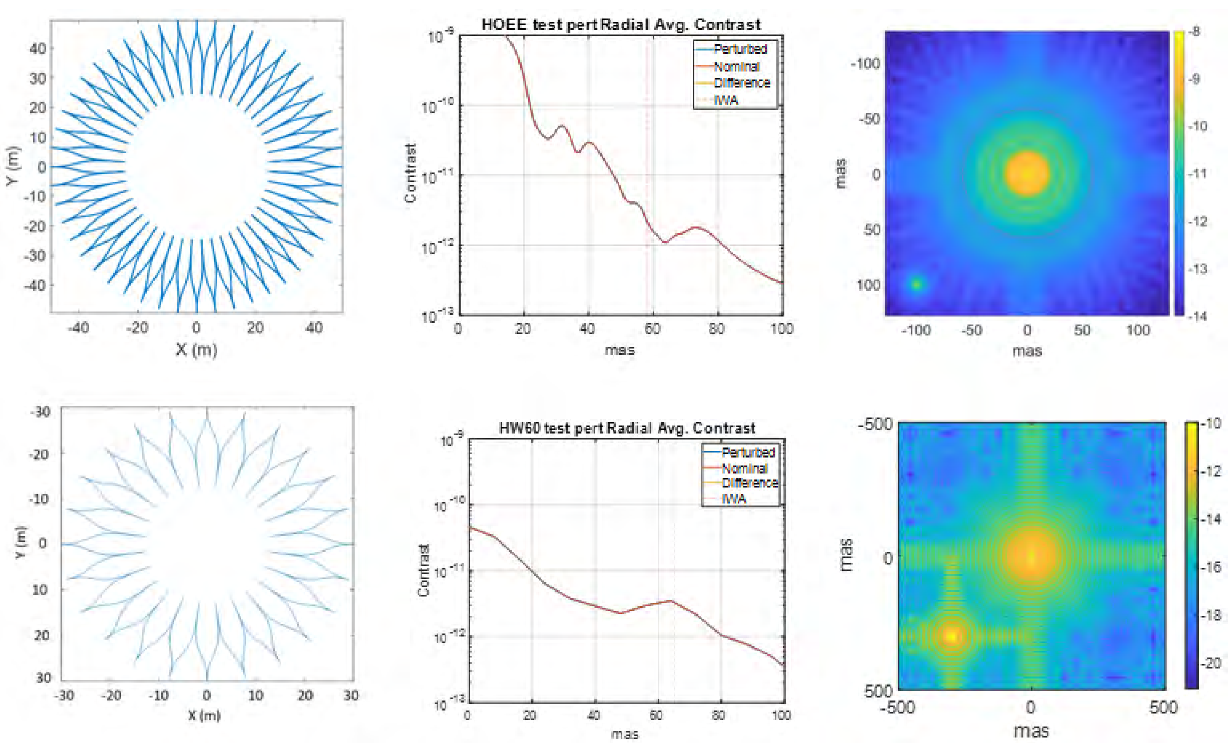

Fig 15 **Top**: The 99 m starshade (HOEE) contrast of nominal case without perturbations. The resulting contrast (yellow curve) is 2×10^{-12} at IWA=58 mas. **Bottom**: The 60 m starshade (HWO) contrast of nominal case without perturbations. The resulting contrast (yellow curve) is 3×10^{-12} at IWA=65 mas.

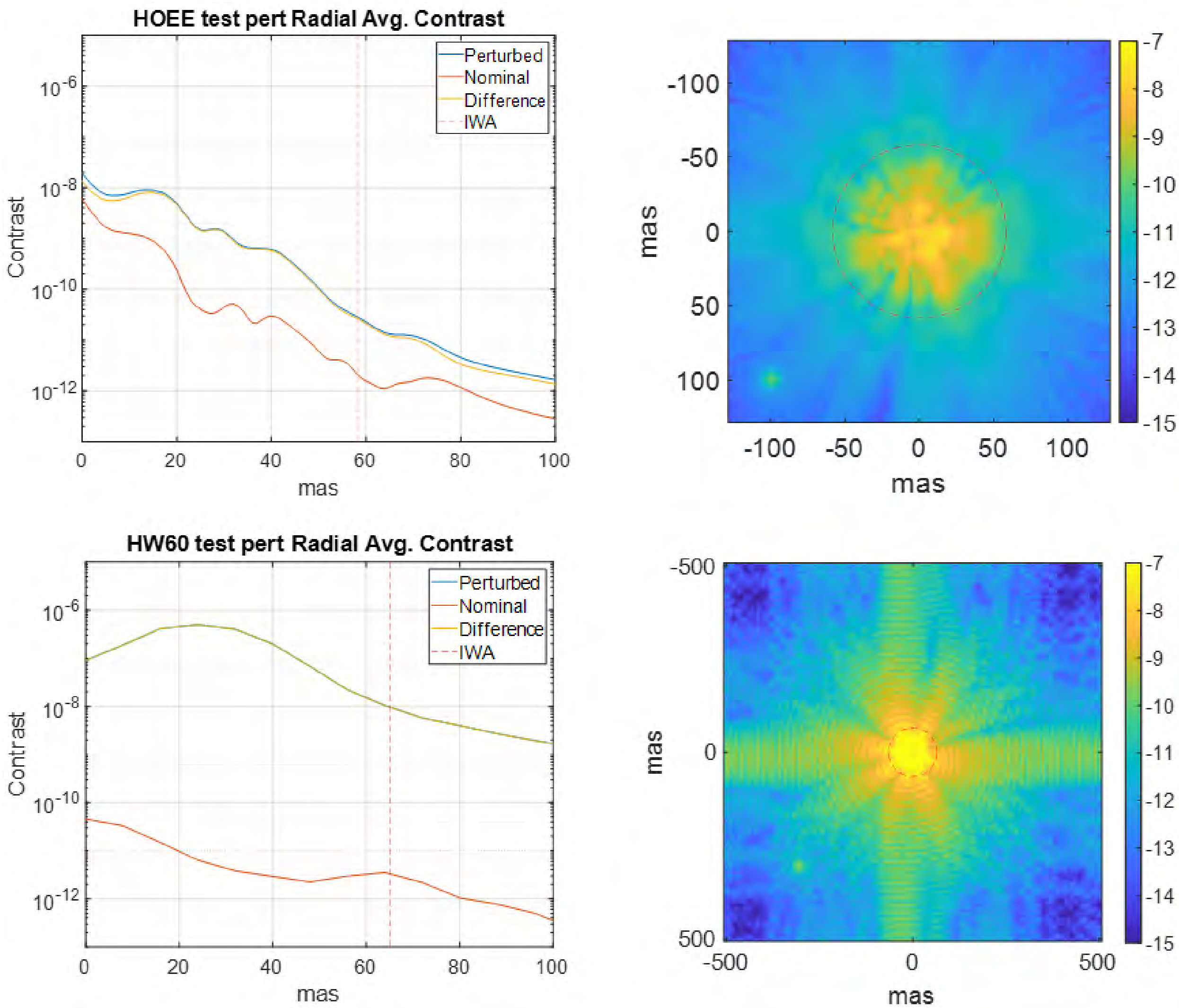

Fig 16 Top: The 99 m starshade (HOEE) contrast of different perturbations combination; petal displacement = 100mm (random & global), segment displacement = 100 um (random & global), and Proportional petal = 500 ppm (length & width). The resulting HOEE contrast (yellow curve) is 3×10^{-11} at IWA=58 mas. **Bottom**: The 60 m starshade (HWO) contrast of different perturbations combination, given the proportional size between both starshades (60/100); petal displacement = 60mm (random & global), segment displacement = 60 um (random & global), and Proportional petal = 500 ppm (length & width). The resulting HWO contrast (yellow curve) is 1×10^{-8} at IWA=65 mas, suggesting that the 99 m starshade for HOEE is more robust and far less sensitive ($>$ 10X in parameter stability), compared than the 60 m starshade for HWO.

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