

# The observation of Earth-like exoplanets with ground-based telescopes and a shared orbiting starshade

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## ABSTRACT

This paper provides the predicted performance of a hybrid space-ground approach that combines a large ground-based telescope such as the Extremely Large Telescope (ELT), the Thirty Meter Telescope (TMT), or the Giant Magellan Telescope (GMT), with a shared orbiting starshade in space. This integration aims to image Earth-like exoplanets around Sun-like stars with deep contrast imaging and an unmatched angular resolution. The starshade forms a deep shadow above the Earth's atmosphere. However, the presence of atmospheric turbulence requires compensation with adaptive optics to sharpen the images to the diffraction limit. In this paper, we present the expected image plane contrast of the three large telescopes operating with a shared orbiting 99 m diameter starshade, with a detailed analysis focusing on the ELT to measure the reflected light spectra of a solar system, from Venus to Saturn, orbiting a sun-like star. Our analysis utilizes a comprehensive and realistic model of the entire system, incorporating the latest ELT Adaptive Optics (AO) models to mitigate the effects of Earth's atmospheric turbulence under moderate weather conditions. Our studies show that the ELT AO effectively corrects for these effects, demonstrating minimal impact on sensitivity with different Strehl Ratios (SR) and throughout the full 300–1000 nm bandpass. This includes a comparison with current and future ground- and space-based observatories. We simulate the reflected light images and spectra through Earth's atmosphere. We show observation of the major molecular signatures for life, such as oxygen and water on an exo-Earth, leading to a promising avenue for future hybrid space-ground observatories to revolutionize the search for Earth-like planets. Near-term advancements for the implementation of this concept toward deployment will be discussed.

## Background

The search for exoplanets around nearby Sun-like stars stands as a core objective of modern astronomy, as described in the National Academy's 2020 Astronomy and Astrophysics Decadal Survey<sup>1</sup>. Astronomers have identified over 6,000 exoplanets<sup>2</sup>, spanning a wide range of sizes and masses, many of which orbit nearby stars. Imaging habitable exoplanets is exceptionally challenging because these planets are extremely faint and orbit their host stars at very close angular separations (<100 mas), making them difficult to distinguish from the stars' bright glare. The current direct imaging space instruments, such as JWST NIRCAM and Roman Space Telescope CGI, are unable to directly observe Earth-like exoplanets. A leading strategy for overcoming these challenges involves constructing a space-based telescope equipped with an internal coronagraph or a starshade to block the star's light. NASA's response to the Decadal Survey has been to study a large space-based telescope equipped with an internal coronagraph - the Habitable World Observatory<sup>3</sup> (HWO) concept. This concept has substantial challenges related to cost, stability, testing, and other technical limitations. Ground-based observatories equipped with extreme adaptive optics and coronagraphs (e.g., SPHERE) have successfully imaged bright exoplanets<sup>4,5</sup>. However, Earth-like exoplanets remain beyond

31 the reach of current ground-based telescopes.

32 The application of a starshade for direct imaging of exoplanets is attributed to R. Danielson in Lyman Spitzer's 1962 treatise  
33 on space astronomy<sup>6</sup>. In 2006, Cash et al.<sup>7</sup> described 60-m diameter flower-shaped occulter with hyper-Gaussian petals  
34 to achieve a sufficiently dark shadow for Exo-earth detection. Vanderbei et al.<sup>8</sup> described the mathematics to optimize the  
35 designs including practical engineering constraints. Jansen<sup>9</sup> first proposed a novel framework for combining a hybrid orbiting  
36 starshade with an extremely large ground-based telescope, and later<sup>10</sup> extended their framework for a 100-meter-class starshade  
37 in conjunction with Extremely Large Telescopes. Mather et al.<sup>11</sup> initiated the Hybrid Observatory for Earth-like Exoplanets  
38 (HOEE) concept, funded by the NASA Innovative Advanced Concepts (NIAC) program<sup>12</sup>. The team<sup>11</sup> assumed that adaptive  
39 optics would eventually enable reasonable efficiency and diffraction limited image quality. The observing speed for a point  
40 source with diffraction limited imaging and background limited sensitivity scales as  $D^4/B$  where  $D$  is the telescope diameter  
41 and  $B$  is the diffuse background level. The planned or possible adaptive optics capabilities of the 39 m ELT<sup>13,14</sup>, 30 m TMT<sup>15</sup>,  
42 and 24 m GMT<sup>16</sup> have further advanced the potential for a hybrid ground-space observatory. The publications highlighted  
43 the orbital mechanics, quantified the necessary propulsion requirements<sup>11,17,18</sup>, analyzed image quality<sup>19</sup>, demonstrated  
44 high performance adaptive optics using an orbiting laser beacon<sup>20</sup>, and the expected optical performance<sup>21</sup>. This concept  
45 enables several advantages over the HWO concept due to the large ground telescope aperture. Our study<sup>21</sup> reports the required  
46 starshade stability is 10x relaxed compared to a starshade for HWO. One of the major challenges in implementing this  
47 concept is the development of advanced adaptive optics systems to correct for atmospheric turbulence. Our recent study<sup>21</sup>  
48 presents a preliminary performance assessment of ELT-class adaptive optics systems, including a tolerance analysis and a  
49 comprehensive evaluation of key background noise sources, such as solar glint, earthshine, and optical interference, along with  
50 the corresponding mitigation strategies required to enhance the feasibility of this approach.

51 In this paper, we introduce a detailed performance analysis that accounts for atmospheric turbulence and evaluates the  
52 effectiveness of the ELT adaptive optics system in mitigating these effects to enable the detection of full exoplanetary systems  
53 and potential biosignatures beyond Earth. We first present the predicted contrast performance of these large ground-based  
54 telescopes (ELT, GMT, and TMT) with an orbiting starshade. We provide a comprehensive contrast analysis with various Strehl  
55 Ratio (SR), over the oxygen and water molecular bands, comparing them with both current and proposed concepts. We focus  
56 on studying the crucial effect of ELT AO to correct for the Earth's atmosphere. Our findings show that this concept allows for  
57 direct imaging of Earth-like planets orbiting Sun-like stars, enabling the acquisition of their spectra and key molecules to search  
58 for signs of life. We also explore the implementation and the deployment of a 99 m starshade in the near future.

## 59 **Expected Performance of ELT/GMT/TMT Observatories with an Orbiting Starshade**

60 The ELT system is being developed for the direct ground-based imaging of bright exoplanets, such as Neptunes and Jupiters.  
61 However, without an orbiting starshade, ground-based telescopes are generally unable to image Earth-like planets orbiting Sun-  
62 like stars. Integrating the ELT with an orbiting starshade would significantly enhance its capability to detect and characterize  
63 such habitable exoplanets. Additionally, the ELT's angular diffraction limit of 3 mas is adequate to distinguish structures, even  
64 those as small as 0.1 AU at a distance of 10 pc.

65 We use the Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)<sup>19</sup> to model the hybrid ground-  
66 starshade concept. The optical model design and performance of the Hybrid Ground-Space Observatory, combining the ELT  
67 on the ground with a 99m diameter orbiting starshade, are described in our work<sup>21</sup>. Figure 1 illustrates how this concept can be  
68 extended to encompass the TMT and GMT telescopes, enabling coverage of numerous sky targets and frequent observations.  
69 The starshade's shape is determined through optimization algorithms<sup>22</sup>, guided primarily by orbital constraints at a distance  
70 of 175,000 km. The starshade features 48 petals each 24.5 m long, and a 50 m diameter central disk. We emphasize that the  
71 deep shadow is formed above the Earth's atmosphere and is not degraded by atmospheric turbulence. Figure 2 illustrates the  
72 predicted contrast performance for each telescope across the entire bandpass. Within the 300–1000 nm wavelength range and  
73 beyond the IWA, the instrument achieves contrast ratios well below approximately  $10^{-10}$  relative to a Sun-like star's brightness  
74 in the habitable zone.

75 This approach (Figures 1 and 2) allows multiple large, geographically distributed ground-based telescopes to operate in  
76 coordination with a single orbiting starshade, enhancing sky coverage and increasing target accessibility while potentially  
77 reducing fuel consumption for starshade retargeting<sup>10,11,18</sup>. Certain targets may also be uniquely visible or more optimally  
78 observed from specific observatory locations. The shared orbiting starshade architecture also enables more efficient retargeting  
79 of the starshade between observatories with more favorable weather conditions for observation. However, only the largest  
80 telescopes will be capable of observing more than a few Earth-like exoplanets, due to the  $D^4$  scaling law governing observing  
81 speed.

## 82 Observing through Earth's Atmosphere and ELT AO Mitigation

83 While the starshade is designed to enable imaging of Earth-like habitable exoplanets, a major optical challenge remains:  
84 atmospheric turbulence, which can degrade image quality. Therefore, it is essential to evaluate the role of a ground telescope's  
85 adaptive optics in correcting for these effects. We incorporate the realistic ELT adaptive optics atmospheric model using Python  
86 package AnisoCADO<sup>23</sup> to generate AO PSFs for the ELT for a given set of atmospheric profiles and weather conditions, and  
87 assess how it can mitigate the blurring caused by the turbulence. This work presents the first proof of concept for extending  
88 similar analyses to other hybrid configurations involving AO atmospheric modeling for both GMT and TMT. The resulting  
89 simulated contrast, full solar system detectability, and spectral response are discussed below.

### 90 Imaging Contrast

91 Figure 3 compares the predicted contrast after incorporating the ELT AO atmospheric model, at varying SR, versus existing and  
92 proposed approaches, at the bandpass limits. The concept achieves orders of magnitude improvement in flux ratios compared to  
93 current instruments and proposed concepts. The SR strongly degrades with shorter wavelength<sup>24,25</sup>. Figure 3 shows that optical  
94 performance remains below  $10^{-10}$  contrast at 300 nm, extending up to 1 micron, over a broad range of SR (0.05 at 300 nm  
95 and 0.5 - 0.75 at 1000 nm). These SR values are closer to the baseline requirements defined for the initial ELT instrument  
96 design<sup>13,14</sup>. The high-performance AO laser guide beacon<sup>20,26</sup> combined with single-conjugate adaptive optics (SCAO) system  
97 will further improve performance. Notably, post-processing techniques can also aid with residual background<sup>27</sup>.

98 In addition, the ELT is planning upgrades, including the ELT Planetary Camera and Spectrograph - PCS<sup>28</sup>. The ELT  
99 system<sup>13,23</sup> includes atmospheric dispersion correctors to further compensate for any atmospheric refractive and dispersive  
100 interferences. A laser beacon is positioned at the center of the starshade for supporting high-performance adaptive optics for the  
101 atmospheric turbulence measurements. This laser guide operates across multiple wavelengths, with customized optical filters  
102 integrated into the ground-based telescope systems<sup>13,15,16,29-31</sup> to suppress interference and extract the desired science signal.

### 103 Full Solar System Observation

104 To demonstrate the effectiveness of this concept, we simulated a 20-minute exposure of a solar system located 17 pc away,  
105 accounting for ELT AO atmospheric turbulence with SR of 0.7 and 0.4, as well as Earthshine and exozodi. The results are  
106 shown in Figure 4. Earthshine, coupled with the slight stellar leakage around the starshade's edge, yields a faint diffuse glow  
107 that is barely visible in the image. The plots illustrate that under moderate weather conditions, the ELT's adaptive optics system  
108 effectively compensates for Earth's atmospheric turbulence, enabling the clear observation of an entire solar system, from Venus  
109 to Saturn. Earth, positioned at 1 AU, lies near the IWA, while Venus remains visible even though it is located within the IWA.

### 110 Spectroscopy

111 We use the Planetary Spectrum Generator tool<sup>32</sup>, and ESO's SkyCalc tool atmospheric scattering, transmission, and emission  
112 to simulate the expected spectra. The Planetary Spectrum Generator tool was adapted to the models<sup>33</sup> using the standard  
113 atmosphere templates for the molecular absorption and scattering of the solar system planets, including the absolute flux  
114 calibration. Simulated spectra of Earth-like-exoplanets are shown in Fig. 5 at a distance of 5 pc and 10 pc. Integration times are  
115 consistent with orbital analyses<sup>10,17</sup> showing that we can observe the solar system for a window of up to a few hours. The  
116 plotted spectra have been simulated<sup>32,33</sup> through the ELT AnisoCADO atmospheric model<sup>23</sup>, with an SR of 0.5 at 750 nm. A  
117 warm Jupiter, warm Neptune, and Earth are included<sup>34</sup>. The error bars represent the signal-to-noise ratio (SNR) calculations  
118 performed after subtracting the sky background, exozodiacal light, and light from both the star and the starshade. The exo-Earth  
119 was modeled without accounting for radial velocity effects on molecular spectral features; the velocity-induced shifts can  
120 help distinguish exoplanet signatures after standard telluric correction<sup>35</sup>. The molecular bands of water, oxygen, and methane  
121 of Earth-like exoplanets at 5 pc are clearly visible at wavelengths < 850 nm. Earth at 10 pc is comparably bright as the sky  
122 background for some wavelengths. However, we expect that all modern observatories will have an integral field spectrograph  
123 (IFS), comparable to those of MUSE at ESO's VLT<sup>36</sup>. This will give us a high-precision spectrum of the sky in the wide field  
124 around the target with an extremely high SNR alongside simultaneous observations of the target. This will allow the observation  
125 of signals fainter than the background itself. These techniques are already used extensively in almost all long wavelength  
126 infrared observations<sup>37</sup>. Post-processing is anticipated to further improve performance and observe targets that are much fainter  
127 than the background by at least a factor of  $10^{27}$ .

128 The implementation of extreme adaptive optics to the ground-based telescopes is expected to further enhance optical  
129 capabilities by increasing efficiency and image quality. Studies are being conducted to develop advanced second-generation  
130 instruments for more precise detection. The PCS instrument<sup>28</sup> for the ELT<sup>30,38</sup>, will combine eXtreme Adaptive Optics (XAO),  
131 coronagraphy, and spectroscopy to enable high-contrast imaging with exceptional spatial resolution. Similarly, the GMT is  
132 planned to be equipped with the MagAO-X instrument<sup>24,39</sup>, a next-generation extreme adaptive optics system designed to

133 deliver high-Strehl, high-contrast imaging at visible wavelengths. These capabilities, combined with the orbiting starshade, will  
134 significantly advance deep-contrast imaging performance, enabling the detection of fainter objects at smaller IWAs.

## 135 **Toward the first hybrid ground-space exoplanet observatory**

136 This hybrid ground-space observatory concept enables unprecedented imaging contrast and angular resolution, even in the  
137 presence of atmospheric turbulence, background noise (e.g., Earthshine, solar glint), and system perturbations<sup>21</sup>. Leveraging  
138 the large apertures of ground-based telescopes, the system achieves high SNR imaging of faint, potentially habitable exo-Earths  
139 within minutes, even at small inner working angles (IWA)<sup>11,18,21</sup>. Previous studies<sup>10,11,18</sup> evaluated alignment, station-keeping,  
140 and orbit management requirements for a 99-meter-class starshade. The concept relies on a long elliptical astro-stationary  
141 orbit to match Earth's rotation, using chemical propulsion for station-keeping and solar electric propulsion for retargeting. The  
142 expected performance will be enhanced with the development of the ELT PCS imager.<sup>28</sup> Its expected residual wavefront error  
143 (WFE) is approximately 80–100 nm, corresponding to a Strehl ratio of 50–60 % at 750 nm. This performance level, which  
144 is used in our analysis, as shown in Figures 3, 4, 5, would significantly increase the scientific return of the proposed hybrid  
145 ground-space observatory concept. Compared to HWO, our concept offers a substantially more cost-effective solution with  
146 exceptional angular resolution, and high tolerance, demonstrating the robustness of the design<sup>21</sup>.

147 With this concept, we can image numerous nearby exoplanetary systems, such as Proxima Centauri b<sup>40</sup>, and obtain spectra  
148 of their Earth-like planets in visible wavelengths by targeting oxygen (O<sub>2</sub>), water (H<sub>2</sub>O) and methane (CH<sub>4</sub>) bands. Especially  
149 the two strong oxygen bands at 680 and 760 nm are seen as a result of the Great Oxygenation Event (GOE)<sup>41</sup> in earth's  
150 atmospheric evolution, and thus are potentially the most important biosignatures<sup>42</sup>. Future work will focus on modelling the  
151 scattered light from binary companion stars and exploring mitigation strategies, including the use of an internal coronagraph in  
152 combination with a starshade and an eXtreme Adaptive Optics (XAO) system to achieve sufficient imaging contrast.

## 153 **Path Forward**

154 Recent advances in starshade optical performance, deployable and adjustable starshade technologies, developed by NASA  
155 centers, NIAC-funded initiatives, and industry partners, are making this challenge increasingly tractable. Laboratory demonstra-  
156 tions of scaled starshades have achieved contrast levels exceeding 10<sup>-10</sup> in testing facilities<sup>43,44</sup>. Origami-inspired and furled  
157 starshade structures, such as those demonstrated in the starshade projects<sup>45-47</sup>, have achieved the ~ 100 micrometer-level  
158 deployment precision required for high-performance starlight suppression. Experiments in formation sensing to better than 1-m  
159 lateral tolerance have also been reported<sup>48</sup>.

160 The key remaining challenge in realizing this concept is the mechanical design and successful deployment of a 99 m  
161 starshade into space. The design should meet the tolerance, mass, error budget requirements and shape accuracy— though recent  
162 work suggests that the shape tolerance may be relaxed compared to HWO<sup>21</sup>. Inflatable and furled designs under development  
163 at NASA Goddard and JPL's ALPS lab<sup>46,49,50</sup> further support scalable deployment. Alternative approaches include robotic  
164 assembly techniques<sup>51</sup>. Current efforts are focused on optimizing the 99-meter, 36-petal starshade design (Fig. 6) for simplified  
165 mechanical deployment. Finally, our team received an award from the Caltech Keck Institute for Space Studies (KISS)<sup>52</sup>  
166 to develop a roadmap for implementing this concept over the coming years. Our interdisciplinary KISS team, comprising  
167 approximately 35 leading experts in science, engineering, and technology, will collaborate to outline a clear implementation  
168 plan into the final KISS report and our key findings will be reported in a future SPIE meeting<sup>53</sup> and follow-up publications. The  
169 KISS study lays the groundwork for next-generation hybrid observatory mission focused on the search for life beyond Earth.

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## 314 **Author contributions statement**

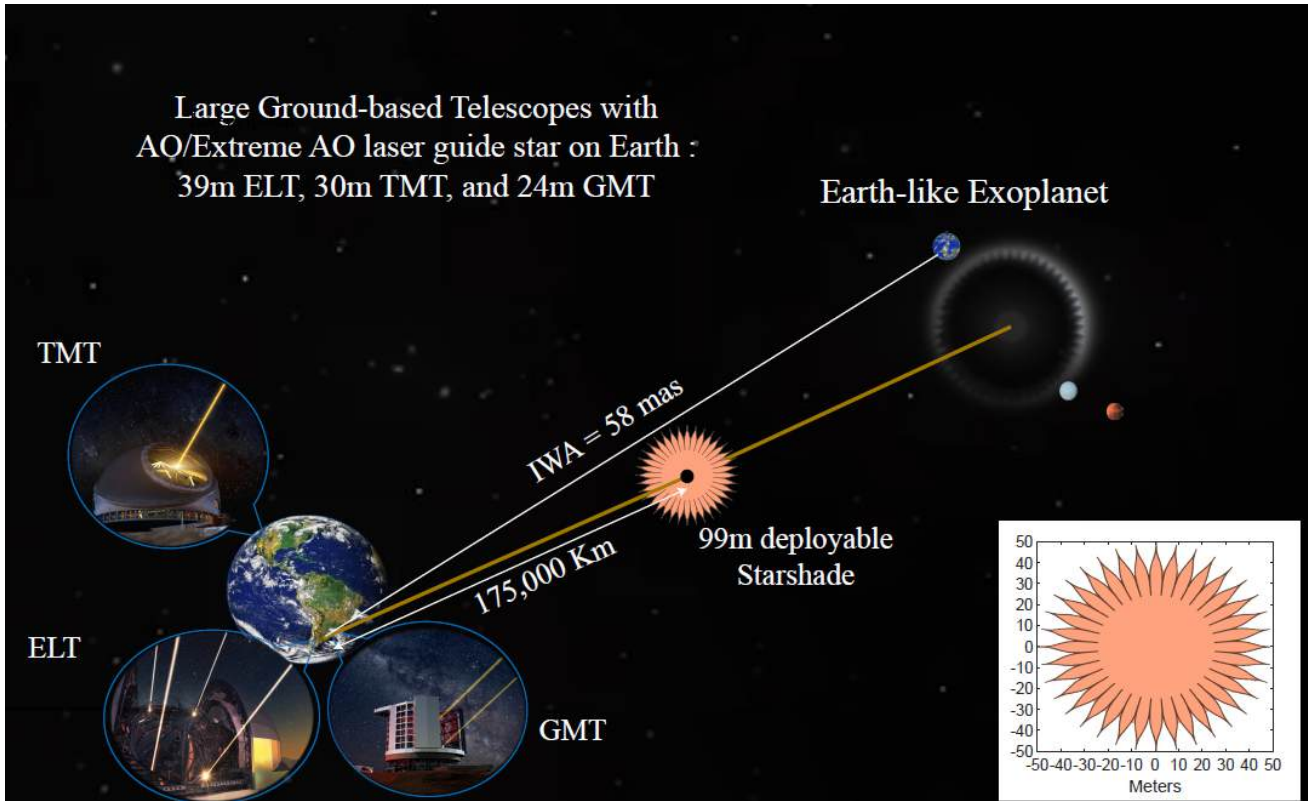
315 J. Mather conceived the NIAC HOEE Phase I study, and shared his study memo materials with A. Soliman. A. Soliman  
316 conducted the technical optical analysis, led the paper studies, wrote the initial version of the manuscript and worked with S.  
317 Shaklan on the starshade diffraction calculations and full paper review. E. Peretz advised on the fuel requirements and orbits. A.  
318 Soliman also contributed the ELT AO PSF inputs and collaborated with S. Kimeswenger, who computed the predicted spectra  
319 of exoplanets. Sara Seager and Michel Mayor provided inputs for exoplanet science and instrument concept. C. Lovis and M.  
320 Cirasuolo provided inputs for ELT AO and XAO. S. Noll helped S. Kimeswenger with the code and basics for the atmosphere  
321 model. All authors reviewed the manuscript and provided scientific insights and suggestions.

## 322 **Competing Interests**

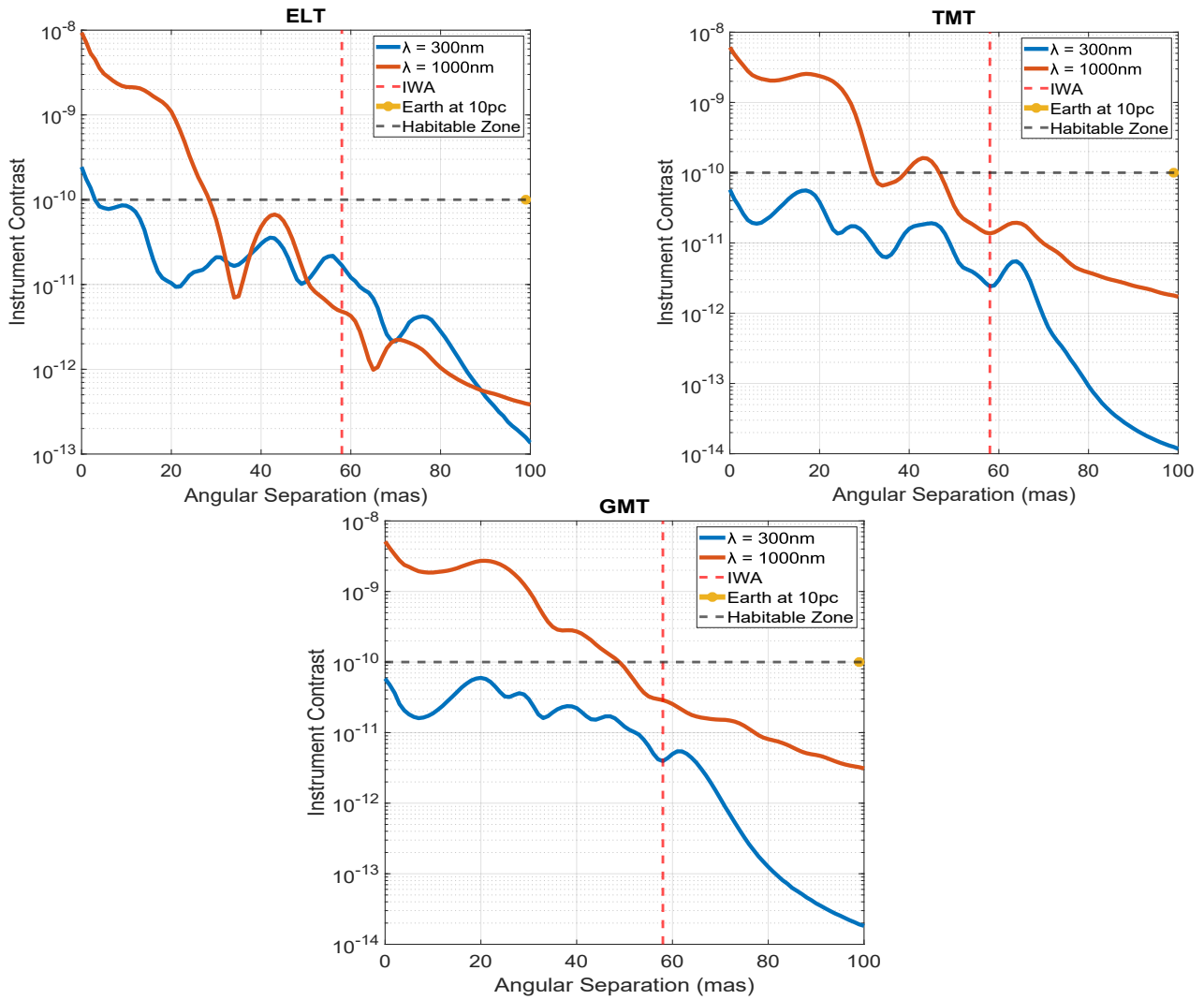
323 The authors declare no competing interests.

## 324 **Data and materials availability**

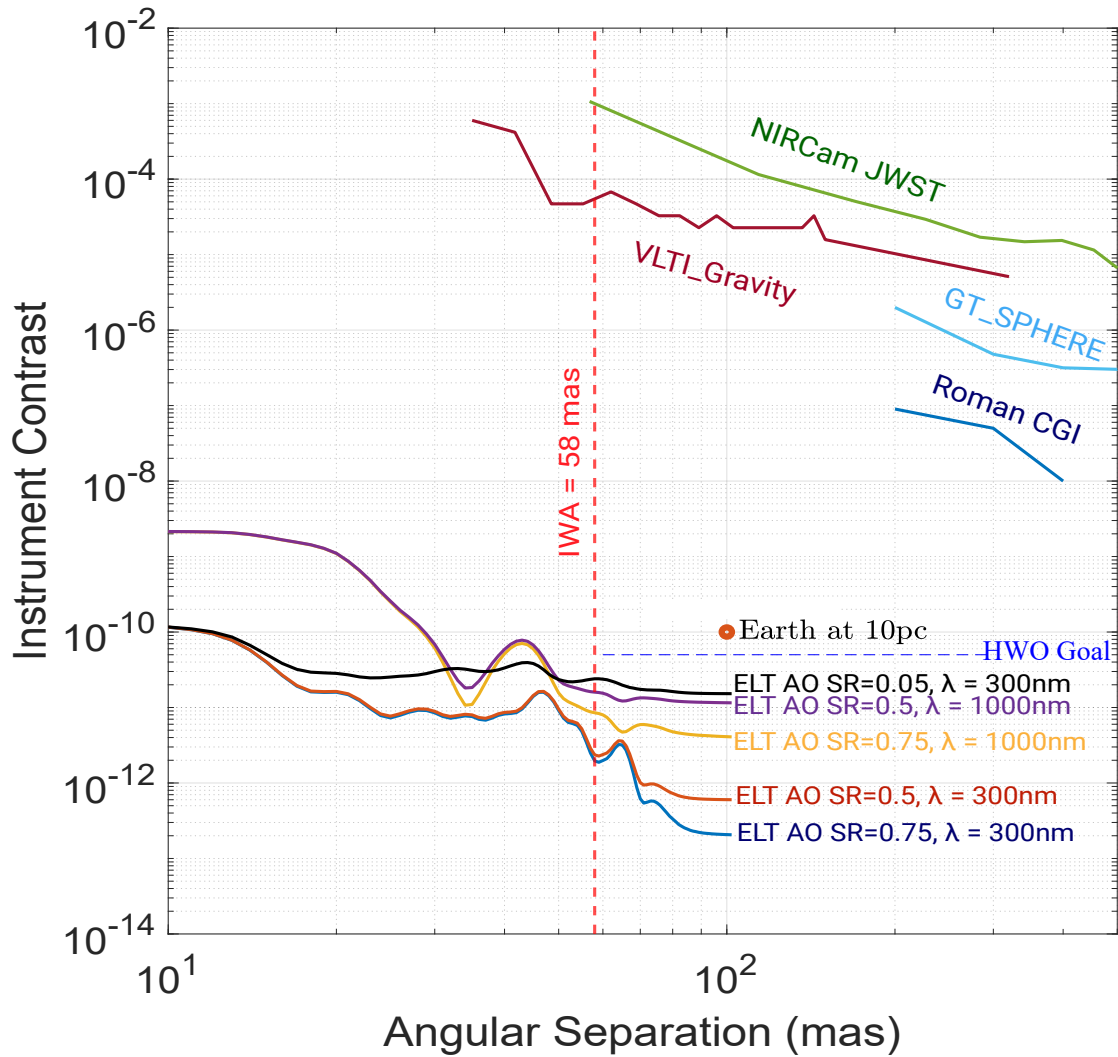
325 All data not included here is available from the authors.



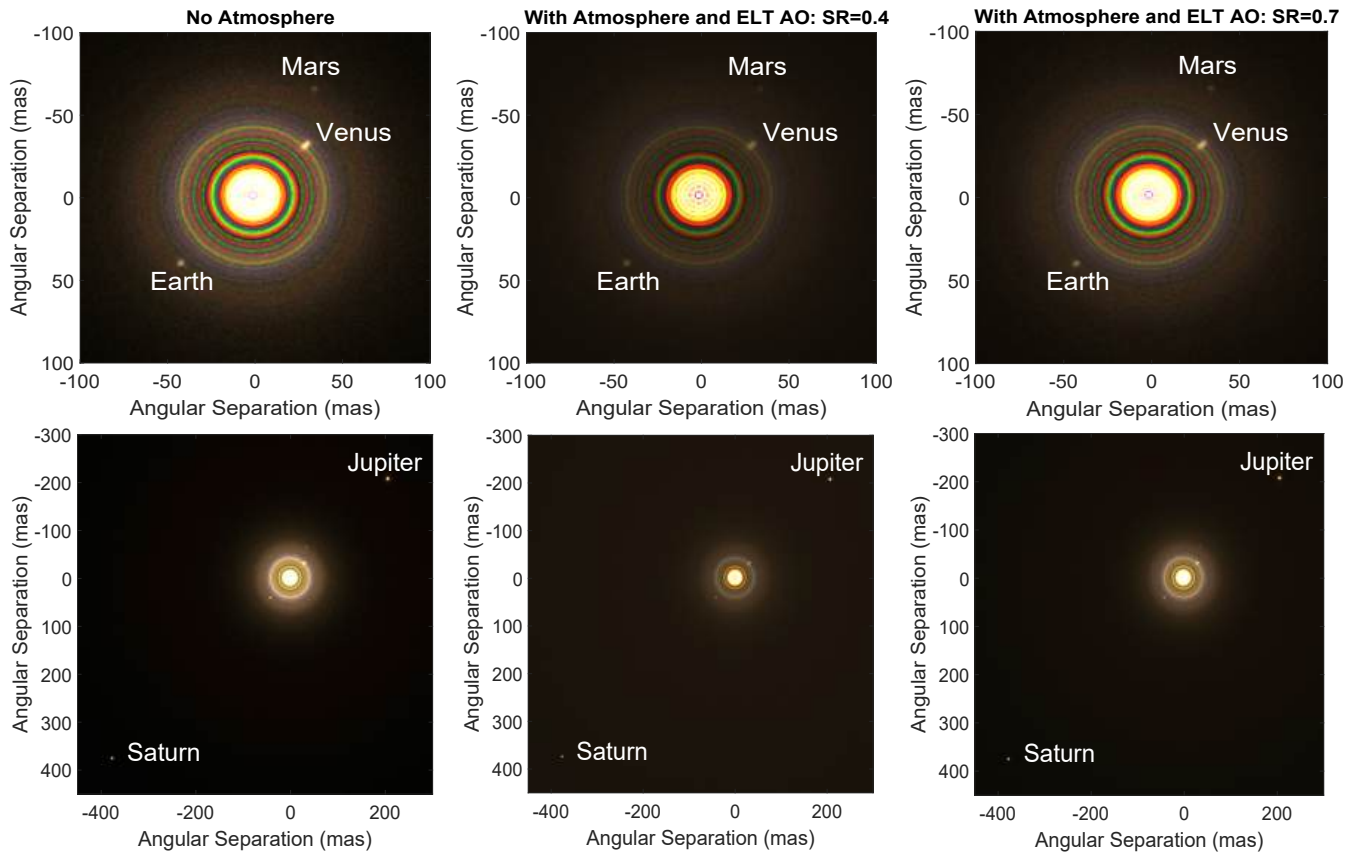
**Figure 1. The Hybrid Ground-Space Observatory concept.** Large ground-based telescopes (ELT, TMT, and GMT) are combined with a shared orbiting starshade to effectively block the glare of the host star and search for Earth-like-Exoplanets. The ELT and GMT are located in Chile, while the TMT is located at Hawaii. The 99 m diameter starshade is positioned in front of the target star, and align with the ground telescopes during the observation. The starshade will be repositioned to align with each telescope, aiming to provide 24-hours of sky coverage and optimized fuel requirements. Axes on the starshade plot are dimensions in meters.



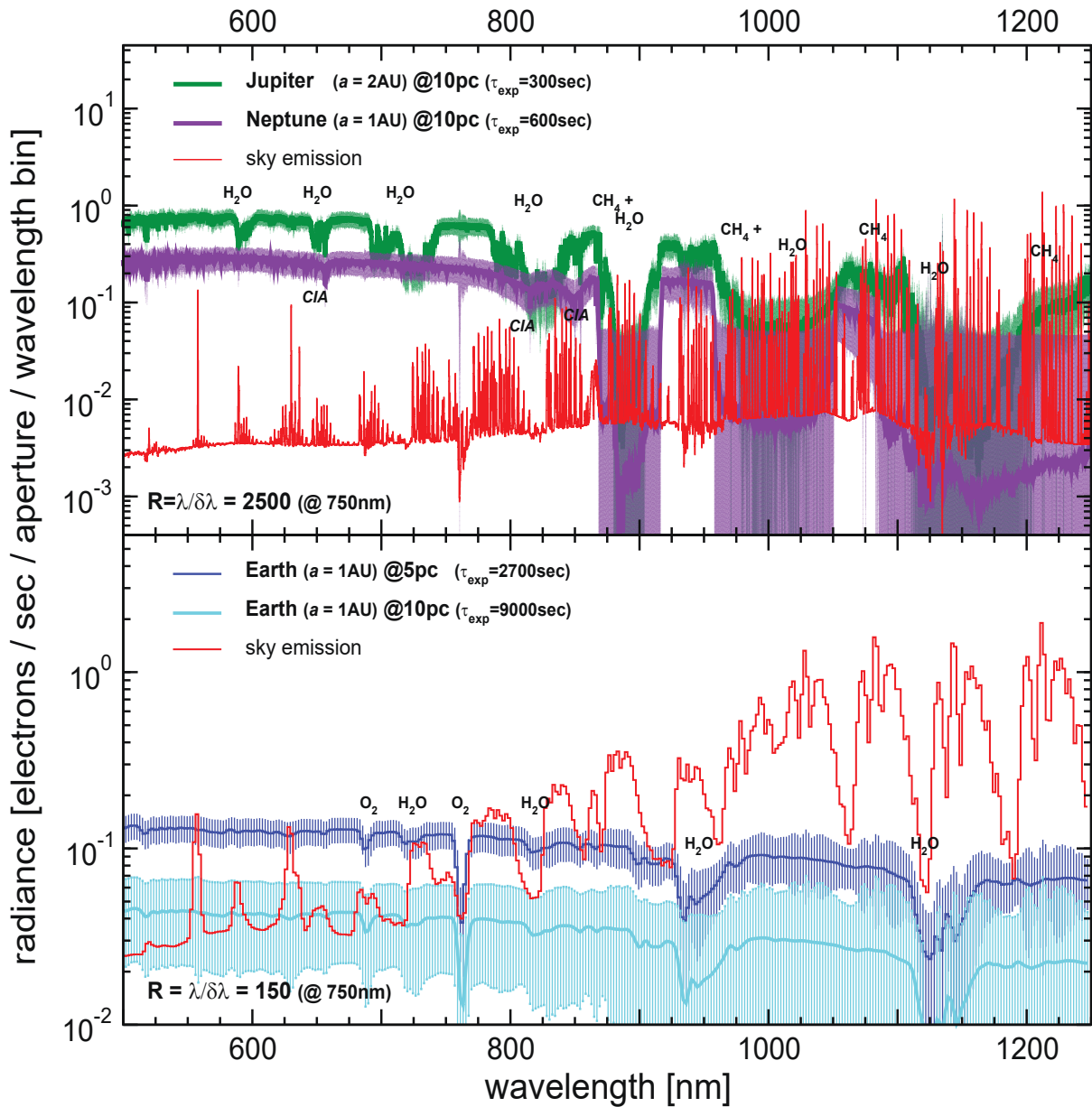
**Figure 2.** The predicted nominal and unperturbed contrast performance for three hybrid ground-space combinations. Vertical dotted lines mark the 58 mas angle, while the horizontal dotted lines at  $10^{-10}$  show the habitable zone requirement to observe Earth-like exoplanets. The orange dots show an example of the Earth-like exoplanet at 10 pc distance. The overall performance is sufficient to image the full solar system, including habitable Earths.



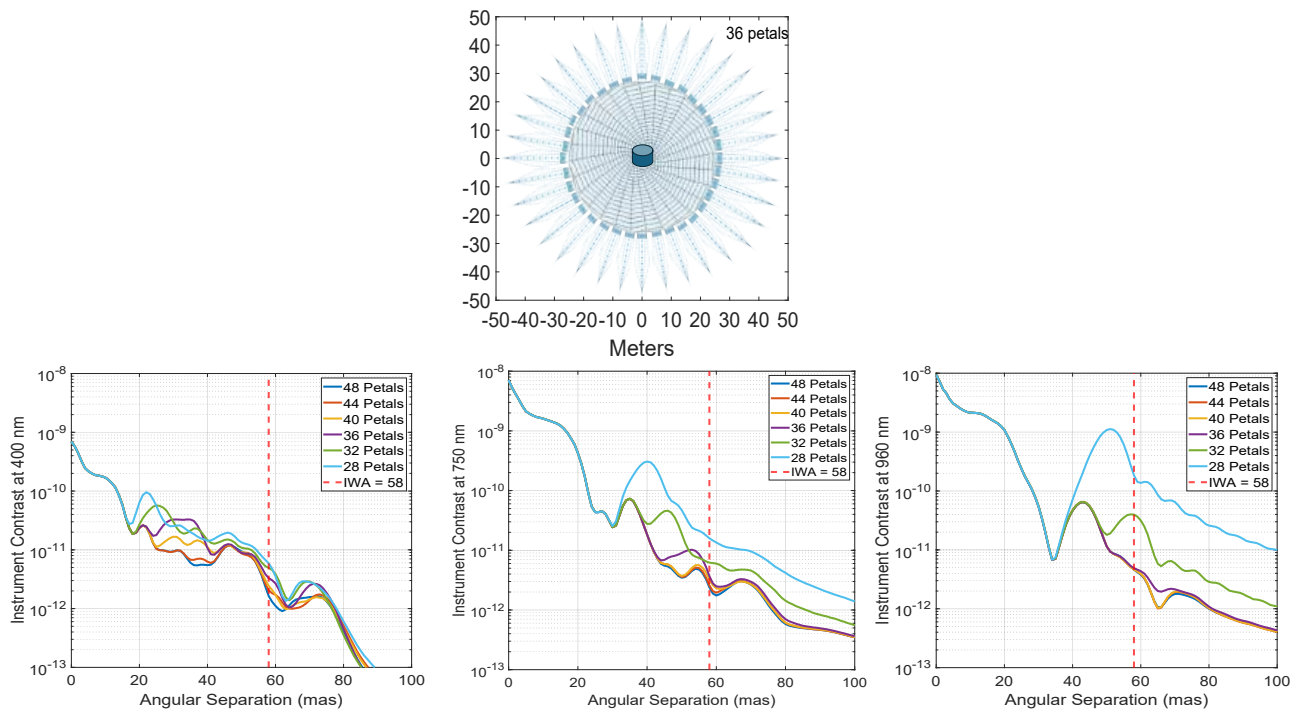
**Figure 3. The predicted performance of the ELT and starshade combination in the presence of the ELT AO atmospheric turbulence.** The plot shows that the ELT AO remains very good over 300-1000 nm and a wide range of SR. The combination shows an exceptional imaging contrast, far better than we need for the observation of Earth-like exoplanets and even fainter objects at smaller IWA. The imaging contrast data for the instruments have been obtained from published work [4, 5, 54, 55](#).



**Figure 4. Simulated Solar System Observations.** Left: Solar system simulation without Earth’s atmosphere. Middle and Right: The simulated performance after we included the ELT atmospheric AO system with  $SR = 0.7$  and  $0.4$ . The plots demonstrate that, under medium weather conditions, the ELT’s adaptive optics system effectively mitigates Earth’s atmospheric turbulence, successfully revealing a full solar system, from Venus to Saturn.



**Figure 5. Simulated spectra for planets at 5 pc and 10 pc with SR = 0.5, including the effect of Earthshine and realistic ELT AO system.** Top panel  $R = \lambda/\delta\lambda = 2500$ , bottom  $R=150$ . 1 pixel =  $\lambda_0/2R = 0.14$  nm for  $R = 2500$  and 2.1 nm for  $R = 150$  at  $\lambda_0 = 750$  nm. Red curves are sky brightness at the ELT in Chile, showing that exo-Earth is brighter than the sky background at certain wavelengths. The plot shows that we could clearly observe the molecular bands of water and oxygen bands of exo-Jupiters, exo-Neptunes and exo-Earths. Widths of curves are  $\pm 1\sigma$ .



**Figure 6. Starshade performance vs. number of petals.** The optimized 99-m starshade features 36 petals for a sufficient optical performance, minimized complexity and a simplifying deployment. Axes dimensions are in meters. Bottom: these plots present the optical performance across the full spectral band for different petal numbers.