PyStarshade: Simulating High-Contrast Imaging of Exoplanets with Starshades

Jamila Taaki [1][¶], **Athol Kemball** [2,3], **and Farzad Kamalabadi**[2]

1 Michigan Institute for Data Science, University of Michigan, USA **2** University of Illinois at Urbana-Champaign, USA **3** University of the Witwatersrand, Johannesburg, South Africa **¶** Corresponding author

Summary

A key challenge in detecting exoplanets and characterizing their atmospheres is distinguishing their faint reflected or emitted light from that of their host stars. Direct imaging addresses this challenge by suppressing the star's light to reveal the orbiting exoplanet. There are two approaches to direct imaging: internal occulters, called *coronagraphs*, which use optics within the telescope to block starlight; and external occulters, called *starshades*, which are petal-shaped masks spanning tens of meters in diameter, flown in tandem with a telescope (Arenberg et al., 2021). Current direct imaging efforts using ground-based coronagraphs at the Very Large Telescope (VLT) and at the Gemini Observatory have successfully imaged young, massive exoplanets at wide separations (Follette, 2023). However, observing a faint, Earth-like planet in the habitable zone of a Sun-like star requires extreme starlight suppression to the level of 10^8 - 10^{10} star-to-planet flux ratio (Angel et al., 1986).

Although no starshade has been flown in space yet, subscale starshades have demonstrated $\leq 10^9$ starlight suppression at a wavelength of 633 nm in laboratory demonstrations (Harness et al., 2021), and $\leq 10^{10}$ across the broad wavelength range necessary for detecting biomarkers such as water, oxygen, and methane in computational simulations (Mennesson et al., 2024). Beyond demonstrating starlight suppression, critical questions remain regarding the properties and orbital configurations of exoplanetary systems that can be observed by starshade missions, as well as optimal instrument designs. PyStarshade is a Python toolbox that efficiently performs optical simulations of starshades with exoplanetary scenes to assess the utility of starshades in future direct-imaging missions.

Several starshade concepts have been proposed but not yet adopted. These include: a 26-meter-diameter design to rendezvous with the Nancy Grace Roman Space Telescope (scheduled for launch in 2026, Romero-Wolf et al., 2021); a 52-meter design as part of the HabEx concept (Gaudi et al., 2020); a 60-meter starshade operating over visible-to-infrared wavelengths (500–1,000 nm) and a 35-meter UV (250–500 nm) starshade, proposed for the Habitable Worlds Observatory (HWO), a NASA mission is in the early design phase, aiming to find and characterize a handful of Earth-like exoplanets (National Academies of Sciences & Medicine, 2023). An example use of PyStarshade to evaluate the complementary role of a 60-meter HWO starshade (Shaklan et al., 2023) paired with two different 6-meter segmented and obscured telescope apertures featuring centimeter-scale details is presented in Taaki et al. (2025), where we report *core throughput* for these apertures. Core throughput is defined as the fraction of exoplanet light recovered and is a key metric that governs the exposure time needed to image an exoplanet and therefore the overall exoplanetary yield of a mission.

Statement of need

PyStarshade provides a toolbox for performing optical simulations from source to focal plane with a configurable starshade telescope design. Complex electric fields are calculated at three planes of propagation: the starshade, the telescope aperture, and the focal plane, using the Fresnel or Fraunhofer diffraction formula where appropriate. First-order imaging characteristics of a starshade can be determined from analytic relations that depend on the size of the starshade, the size of the telescope aperture, the wavelength of the observations, and the flight distance. PyStarshade allows for second-order imaging characteristics to be studied, including imaging simulations with a pixelized exoplanetary input scene of integrated flux per pixel and wavelength. It also allows for the study of throughput and post-processing methods with varying starshade masks and telescope aperture masks to study throughput and post-processing methods. An example imaged scene is shown in Figure 1 at a snapshot in time and wavelength. The scene consists of a planet, a star, and a dust disk. These spectral- and time-dependent scenes were generated with ExoVista (Stark, 2022). PyStarshade is intended to be flexible and efficient in studying exoplanet retrievals and instrument design.
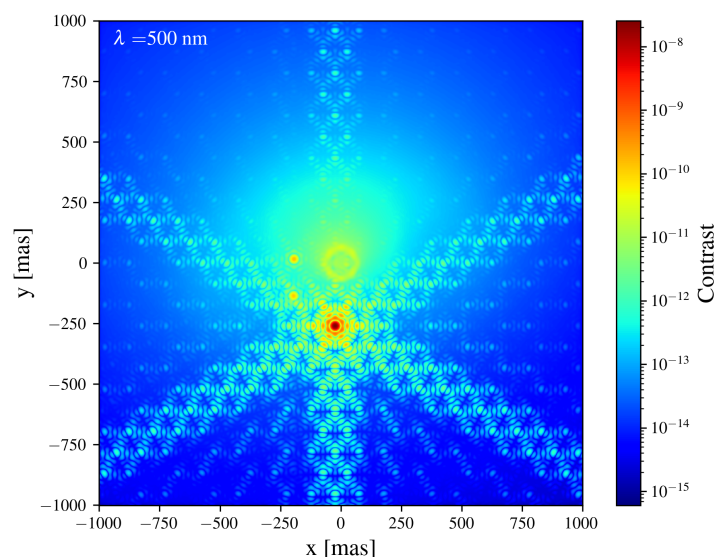

Figure 1: A starshade imaging simulation shown at a wavelength of 500 nm with a synthetic exoplanetary input scene (generated with ExoVista). Three exoplanets are directly visible, while two more sit inside the starshade suppression zone. The scene assumes a 60 m HWO starshade paired with a 6 m segmented telescope; the planets in the scene have planet-to-star flux ratios between 10^{-8} and 10^{-10}.

Fourier optics simulations of starshades and telescope apertures require fine spatial pixel scales to accurately model diffraction without aliasing errors across multiple stages of propagation. Traditional fast Fourier transforms (FFTs) require large zero-padding factors to accomplish this, increasing computational cost. PyStarshade implements the Bluestein FFT (Bluestein, 1970, related to the chirp Z-transform) to compute optical fields at arbitrary spatial scales without zero-padding, thereby achieving greater efficiency than the FFTs or discrete Fourier transforms (DFTs). PyStarshade implements the Bluestein FFT using NumPy (Harris et al., 2020) FFTs and array operations.

Furthermore, PyStarshade implements a novel technique to chunk Bluestein FFT calculations, which mitigates memory bottlenecks. A set of unit tests is provided to validate the Fourier diffraction tools. PyStarshade precomputes fields, point spread functions, and throughput grids for different stages of the optical propagation chain. This allows flexibility in modifying instrument parameters or telescope aperture masks. PyStarshade optionally interfaces with

HCIPy ([Por et al., 2018](#)) to generate telescope apertures and the resulting imaging.

Related software

The Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (`SISTER`, [Hildebrandt et al., 2021](#)), implemented in MATLAB, performs detailed, end-to-end simulations of starshade imaging, further including instrument noise sources such as solar glint, and tools for modeling an exoplanetary system and background objects. The optical simulation pipeline of `PyStarshade` follows a similar approach to that of `SISTER`, employing a precomputed point spread function (PSF) basis for image simulation. However, `SISTER` computes diffraction from the starshade to the telescope aperture using the boundary diffraction wave method ([Cady, 2012](#)), performing a 1D integral along the starshade's edge, followed by a DFT to obtain the final PSF basis. Several other libraries focus exclusively on calculating the starshade diffraction incident on the telescope aperture. One such library is `fresnaq`, a MATLAB library that efficiently computes diffraction by a starshade via the non-uniform FFT ([Barnett, 2021](#)). `diffraq` ([Harness, 2021](#)) is a Python implementation of `freqnaq`. This library also provides an implementation of the boundary diffraction wave method and tools to generate starshade masks ([Harness et al., 2018](#)). The starshade masks used in `PyStarshade` are obtained from `SISTER` or were generated with `diffraq`. Outside of imaging simulations, the Exoplanet Open-Source Imaging Mission Simulator (`EXOSIMS`, [Savransky & Garrett, 2016](#)) provides methods for orbital simulation of starshades and fuel consumption calculations.

Acknowledgements

References

Angel, J. R. P., Cheng, A. Y. S., & Woolf, N. J. (1986). A space telescope for infrared spectroscopy of Earth-like planets. *Nature*, *322*(6077), 341–343. https://doi.org/10.1038/322341a0

Arenberg, J. W., Harness, A. D., & Jensen-Clem, R. M. (2021). Special section on starshades: Overview and a dialogue. *Journal of Astronomical Telescopes, Instruments, and Systems*, *7*(2), 021201. https://doi.org/10.1117/1.JATIS.7.2.021201

Barnett, A. H. (2021). Efficient high-order accurate Fresnel diffraction via areal quadrature and the nonuniform fast Fourier transform. *Journal of Astronomical Telescopes, Instruments, and Systems*, *7*(2), 021211. https://doi.org/10.1117/1.JATIS.7.2.021211

Bluestein, L. (1970). A linear filtering approach to the computation of discrete Fourier transform. *IEEE Transactions on Audio and Electroacoustics*, *18*(4), 451–455. https://doi.org/10.1109/TAU.1970.1162132

Cady, E. (2012). Boundary diffraction wave integrals for diffraction modeling of external occulters. *Optics Express*, *20*(14), 15196–15208. https://doi.org/10.1364/OE.20.015196

Collaboration, A., Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., & others. (2013). Astropy: A community Python package for astronomy. *Astronomy & Astrophysics*, *558*, A33. https://doi.org/10.1051/0004-6361/201322068

Collette, A. (2013). *Python and HDF5*. O'Reilly.

Follette, K. B. (2023). An introduction to high contrast differential imaging of exoplanets and disks. *Publications of the Astronomical Society of the Pacific*, *135*(1051), 093001. https://doi.org/10.1088/1538-3873/aceb31

Gaudi, B. S., Seager, S., Mennesson, B., Kiessling, A., Warfield, K., Cahoy, K., Clarke, J. T., Domagal-Goldman, S., Feinberg, L., Guyon, O., Kasdin, J., Mawet, D., Plavchan, P., Robinson, T., Rogers, L., Scowen, P., Somerville, R., Stapelfeldt, K., Stark, C., … Zellem, R. (2020). The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Final Report. *arXiv e-Prints*, arXiv:2001.06683. https://doi.org/10.48550/arXiv.2001.06683

Harness, A. (2021). *Diffraq: Diffraction with areal quadrature* (Version a61613a). https://github.com/harnessa/diffraq

Harness, A., Shaklan, S., Cash, W., & Dumont, P. (2018). Advances in edge diffraction algorithms. *Journal of the Optical Society of America A*, *35*(2), 275–285. https://doi.org/10.1364/JOSAA.35.000275

Harness, A., Shaklan, S., Willems, P., Kasdin, N. J., Balasubramanian, B. K., Dumont, P., White, V., Yee, K., Muller, R., & Galvin, M. (2021). Optical verification experiments of sub-scale starshades. *Journal of Astronomical Telescopes, Instruments, and Systems*, *7*(2), 021207. https://doi.org/10.1117/1.JATIS.7.2.021207

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hildebrandt, S. R., Shaklan, S. B., Cady, E. J., & Turnbull, M. C. (2021). Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance. *Journal of Astronomical Telescopes, Instruments, and Systems*, *7*, 021217. https://doi.org/10.1117/1.JATIS.7.2.021217

Krekel, H., Oliveira, B., Pfannschmidt, R., Bruynooghe, F., Laugher, B., & Bruhin, F. (2004). *Pytest 7.4*. https://github.com/pytest-dev/pytest.

Mennesson, B., Belikov, R., Por, E., Serabyn, E., Ruane, G., Riggs, A. J. E., Sirbu, D., Pueyo, L., Soummer, R., Kasdin, J., Shaklan, S., Seo, B.-J., Stark, C., Cady, E., Chen, P., Crill, B., Fogarty, K., Greenbaum, A., Guyon, O., … Zimmerman, N. (2024). Current laboratory performance of starlight suppression systems and potential pathways to desired Habitable Worlds Observatory exoplanet science capabilities. *Journal of Astronomical Telescopes, Instruments, and Systems*, *10*(3), 035004. https://doi.org/10.1117/1.JATIS.10.3.035004

National Academies of Sciences, Engineering, & Medicine. (2023). *Pathways to discovery in astronomy and astrophysics for the 2020s*. The National Academies Press. https://doi.org/10.17226/26141

Por, E. H., Haffert, S. Y., Radhakrishnan, V. M., Doelman, D. S., van Kooten, M., & Bos, S. P. (2018). High Contrast Imaging for Python (HCIPy): An open-source adaptive optics and coronagraph simulator. In L. M. Close, L. Schreiber, & D. Schmidt (Eds.), *Adaptive optics systems VI* (Vol. 10703, p. 1070342). https://doi.org/10.1117/12.2314407

Python Packaging Authority. (2024). *setuptools: Easily download, build, install, upgrade, and uninstall python packages*.

Romero-Wolf, A., Bryden, G., Seager, S., Kasdin, N. J., Booth, J., Greenhouse, M., Lisman, D., Macintosh, B., Shaklan, S., Vess, M., Warwick, S., Webb, D., Ziemer, J., Gray, A., Hughes, M., Agnes, G., Arenberg, J. W., Bradford, S. C., Fong, M., … Stark, C. (2021). Starshade rendezvous: exoplanet sensitivity and observing strategy. *Journal of Astronomical Telescopes, Instruments, and Systems*, *7*(2), 021210. https://doi.org/10.1117/1.JATIS.7.2.021210

Savransky, D., & Garrett, D. (2016). WFIRST-AFTA coronagraph science yield modeling with EXOSIMS. *Journal of Astronomical Telescopes, Instruments, and Systems*, *2*, 011006. https://doi.org/10.1117/1.JATIS.2.1.011006

Shaklan, S., McKeithen, D., Lisman, D., & Dumont, P. (2023). A starshade for NASA's Habitable Worlds Observatory concept: exoplanet characterization in the UV. In G. J. Ruane (Ed.), *Techniques and instrumentation for detection of exoplanets XI* (Vol. 12680, p. 1268010). International Society for Optics; Photonics; SPIE. https://doi.org/10.1117/12.2677793

Stark, C. C. (2022). ExoVista: A suite of planetary system models for exoplanet studies. *The Astronomical Journal*, *163*(3), 105. https://doi.org/10.3847/1538-3881/ac45f5

Taaki, J. S., Kamalabadi, F., Kemball, A. J., Corrales, L., & Hero, A. O. (2025). *Efficient exoplanet imaging simulations of the Habitable Worlds Observatory*.

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., & others. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2