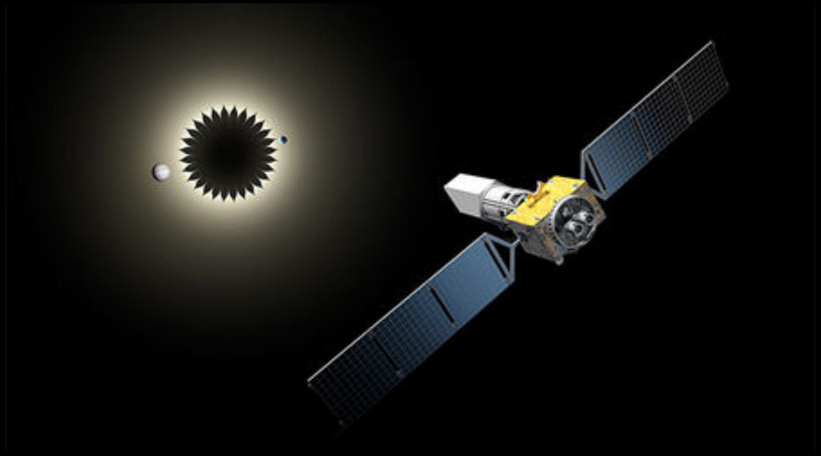
SISTER: Imaging Exoplanets with Starshade

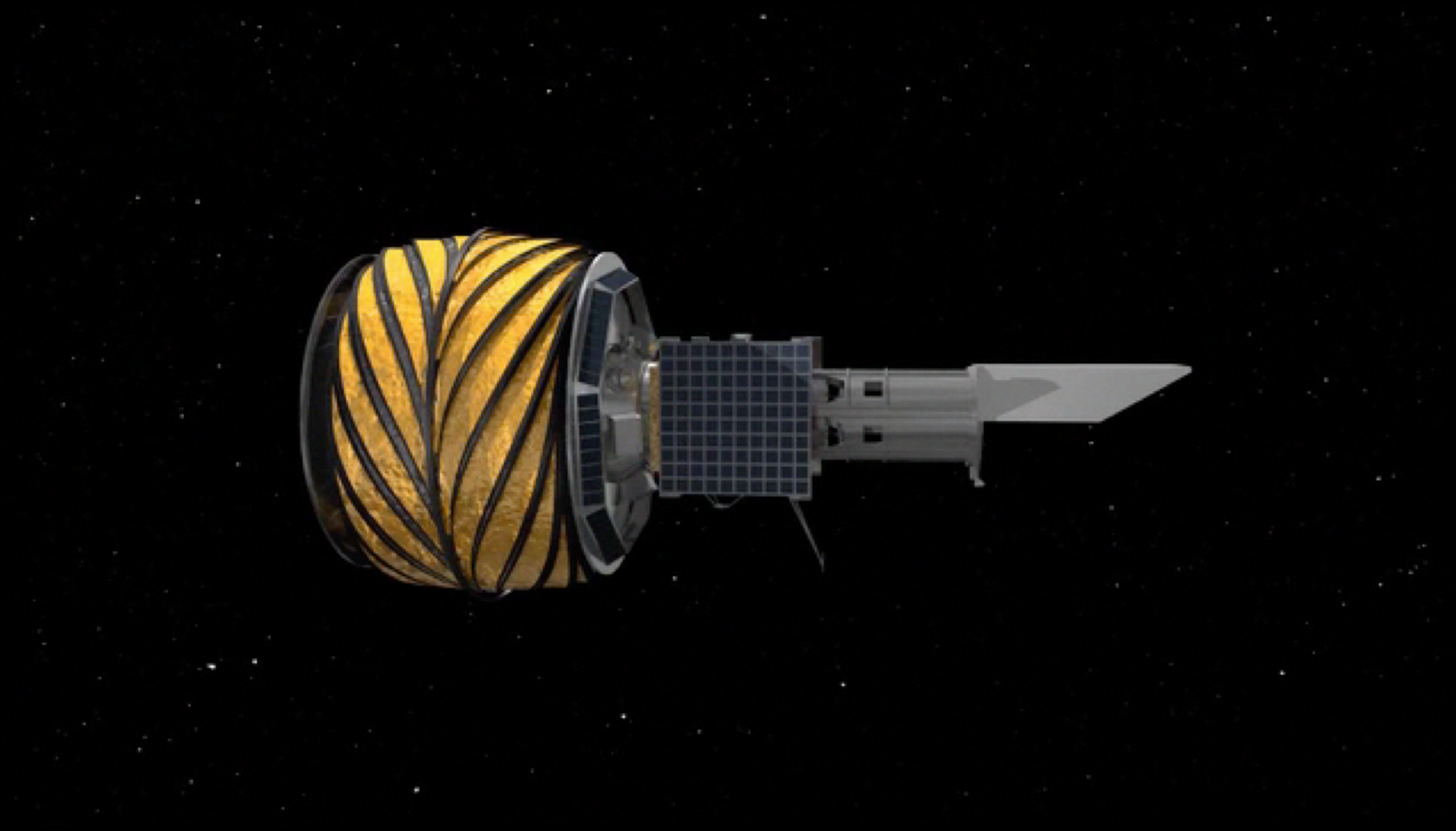


Exoplanet Technology Web Colloquium

Sergi R. Hildebrandt, JPL/Caltech

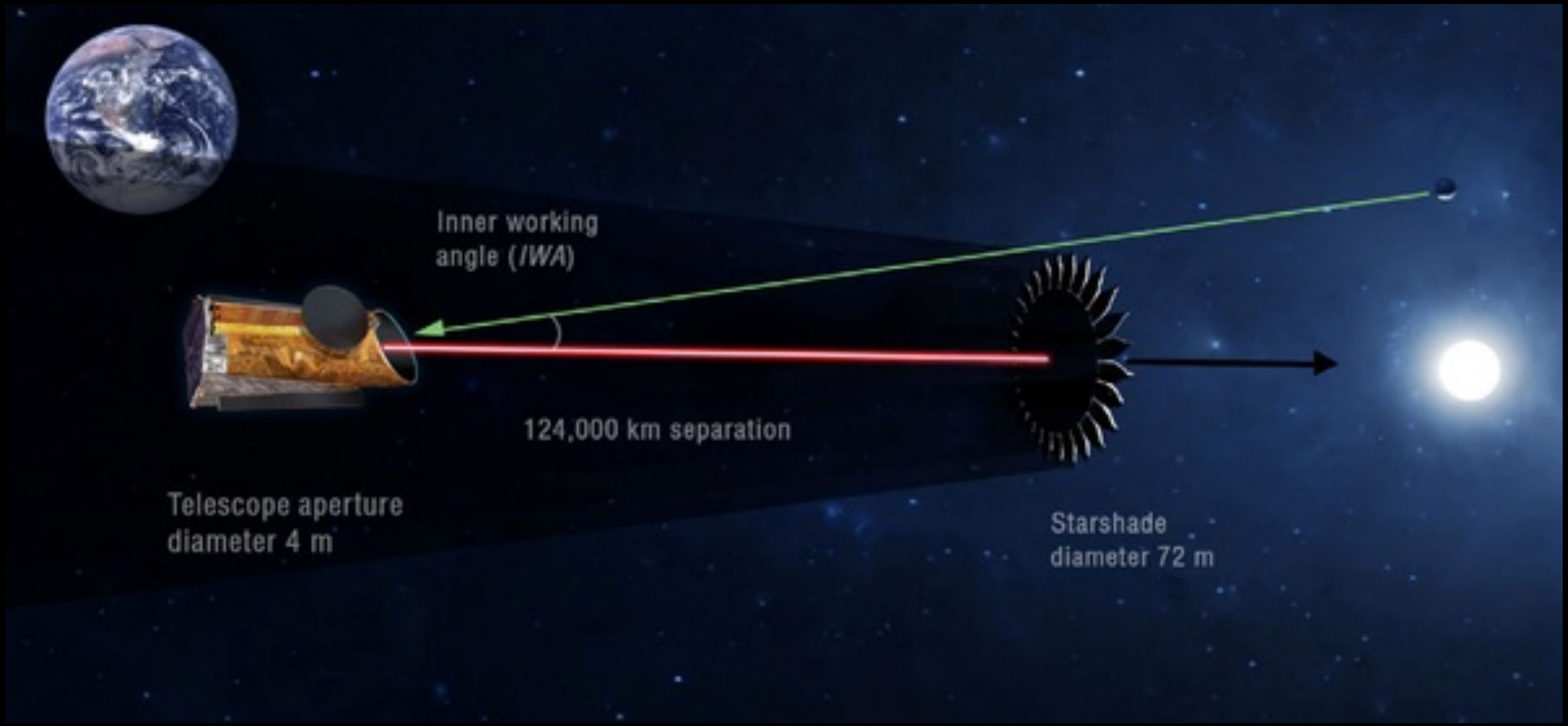
04/11/19

Starshade in a movie

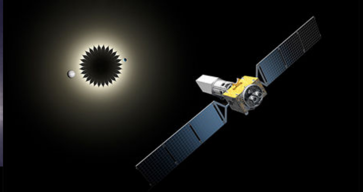


Starshade geometry

Example: Habitable Exoplanet Observatory (HabEx) 2018 design

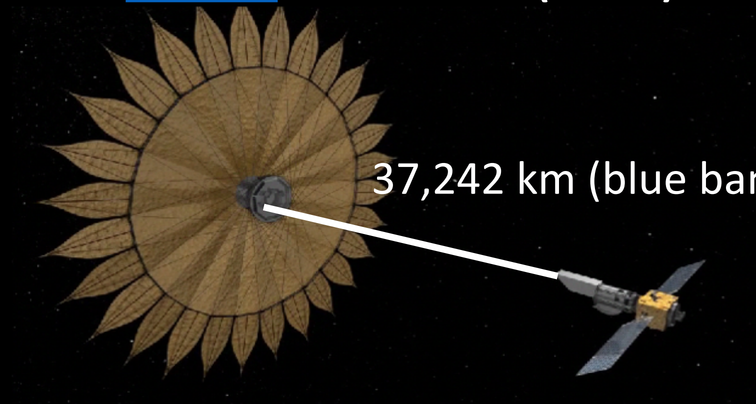


Starshade geometric IWA is only **60** mas.
Same angular size as Earth's semi-major axis at 54 light years.



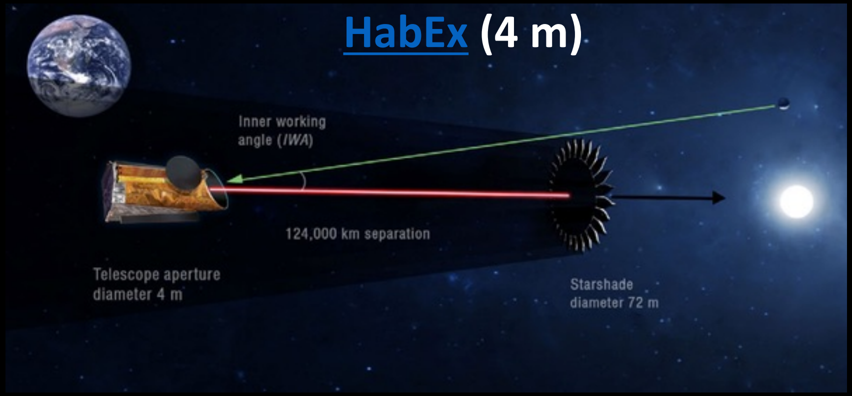
Starshade: Mission Studies

WFIRST Rendezvous (2.4 m)

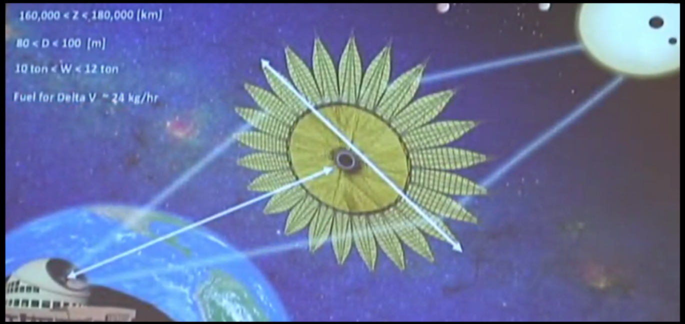


Not to scale

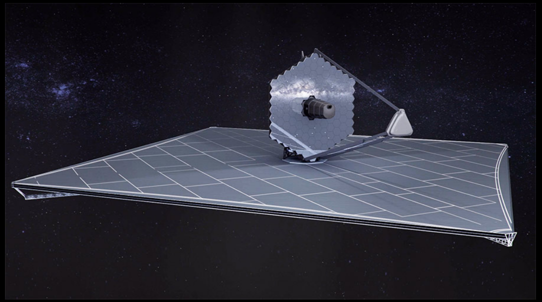
HabEx (4 m)



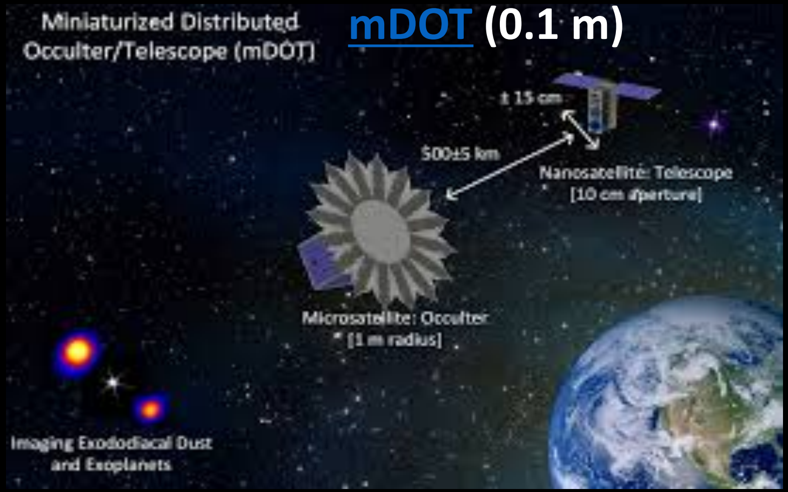
Ground telescopes (30-40 m)



LUVOIR B (8 m)

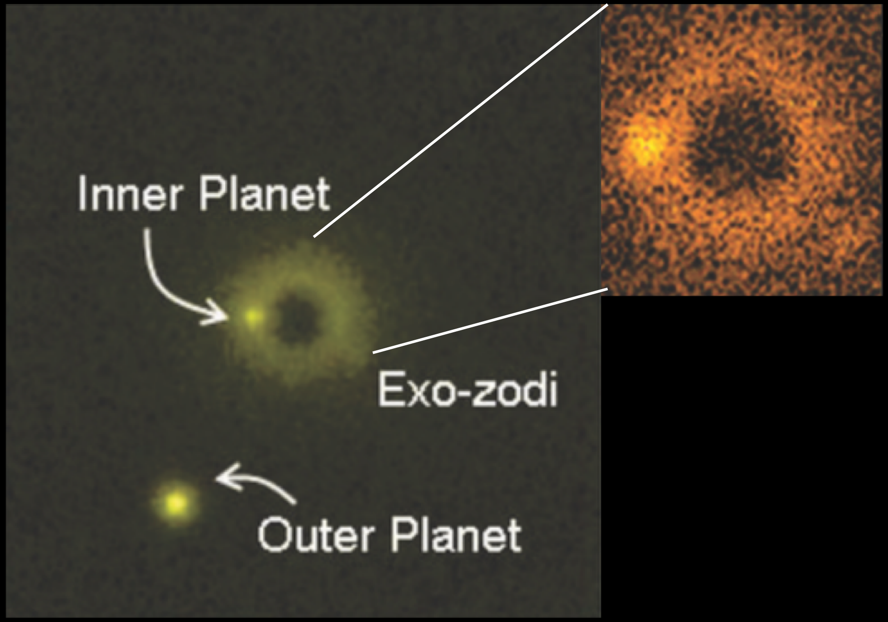


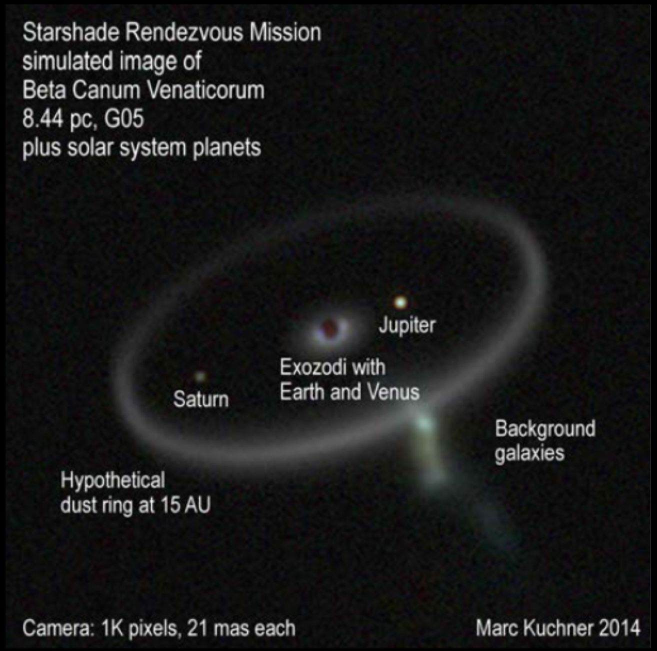
mDOT (0.1 m)

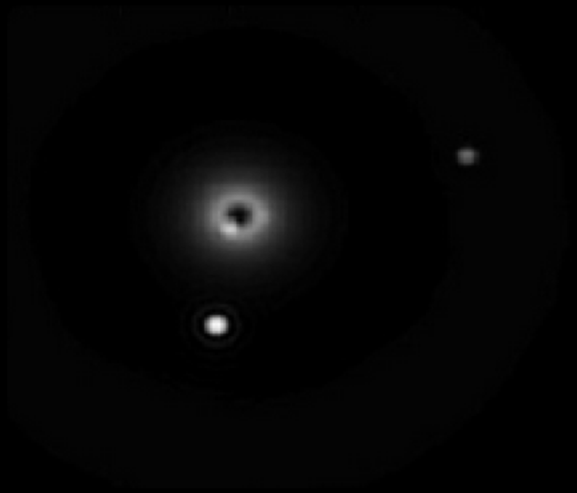


Starshade: Simulations

A few, specific examples. No general user interface.



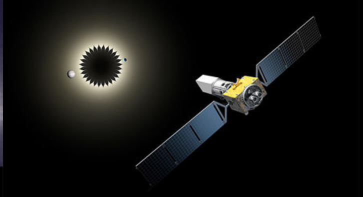




[Lillie et al. SPIE News 2008]

[Exo-S Mission Study 2014]

[M. Hu,, A. Harness,,and N. J. Kasdin SPIE 2017]



SISTER

SISTER (Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance) is a versatile tool designed to provide enough accuracy and variety of starshade astrophysical simulations.*

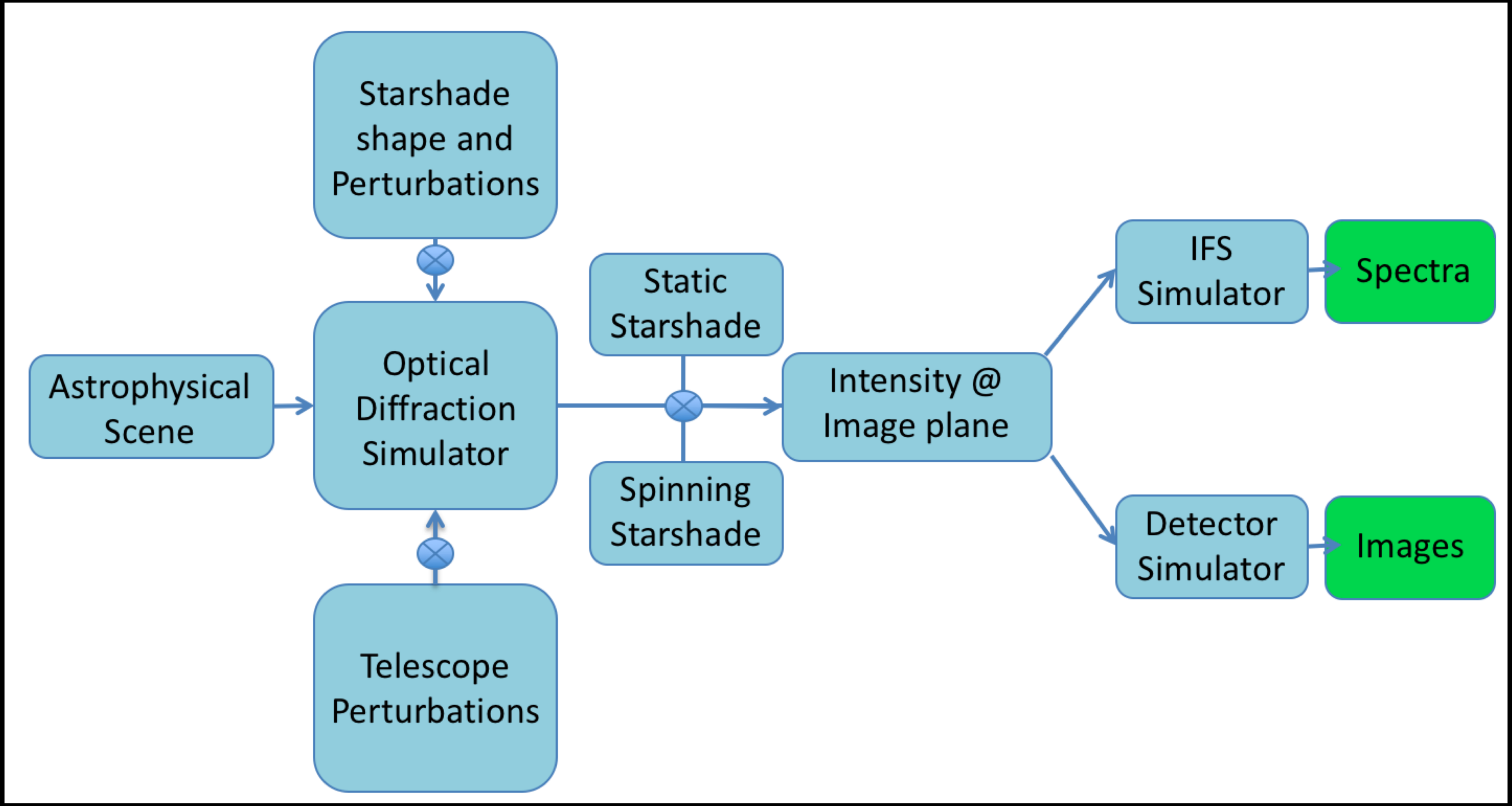
It allows for controlling a set of parameters of the whole instrument that have to do with: (1) the starshade design, (2) the exoplanetary system, (3) the optical system (telescope) and (4) the detector (camera).

There is a built-in plotting software added, but the simulations may be stored on disk and plotted with any other software.

SISTER is an open source project that will evolve with starshade.

(*) **S.R. Hildebrandt**[1] **S.B. Shaklan**[1], **E.J. Cady**[1], and **M.C. Turnbull**[2,1]. (1) Jet Propulsion Laboratory, California Institute of Technology (2) SETI Institute, Carl Sagan Center for Life in the Universe

SISTER Cartoon



Optical Diffraction

Boundary diffraction wave integrals for diffraction modeling of external occulters

Eric Cady*
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109 USA
*eric.j.cady@jpl.nasa.gov

Abstract: An occulter is a large diffracting screen which may be flown in conjunction with a telescope to image extrasolar planets. The edge is shaped to minimize the diffracted light in a region beyond the occulter, and a telescope may be placed in this dark shadow to view an extrasolar system with the starlight removed. Errors in position, orientation, and shape of the occulter will diffract additional light into this region, and a challenge of modeling an occulter system is to accurately and quickly model these effects. We present a fast method for the calculation of electric fields following an occulter, based on the concept of the boundary diffraction wave: the 2D structure of the occulter is reduced to a 1D edge integral which directly incorporates the occulter shape, and which can be easily adjusted to include changes in occulter position and shape, as well as the effects of sources—such as exoplanets—which arrive off-axis to the occulter. The structure of a typical implementation of the algorithm is included.

OCIS codes: (050.1940) Diffraction; (050.1970) Diffractive optics; (070.7345) Wave propagation; (120.6085) Space instrumentation; (350.6090) Space optics.

References and links

1. N. J. Kasdin, D. N. Spergel, R. J. Vanderbei, D. Lisman, S. Shaklan, M. Thomson, P. Walkemeyer, V. Bach, E. Oakes, E. Cady, S. Martin, L. Marchen, B. Macintosh, R. E. Rudd, J. Mikula, and D. Lynch, "Advancing technology for starlight suppression via an external occulter," Proc. SPIE **8151**, 81510J (2011).
2. S. B. Shaklan, M. C. Noecker, T. Glassman, A. S. Lo, P. J. Dumont, N. J. Kasdin, E. J. Cady, R. Vanderbei, and P. R. Lawson, "Error budgeting and tolerancing of starshades for exoplanet detection," Proc. SPIE **7731**, 77312G (2010).
3. T. Glassman, A. Johnson, A. Lo, D. Dailey, H. Shelton, and J. Vogrin, "Error analysis on the NWO starshade," Proc. SPIE **7731**, 773150 (2010).
4. R. J. Vanderbei, E. J. Cady, and N. J. Kasdin, "Optimal occulter design for finding extrasolar planets," Astrophys. J. **665**, 794–798 (2007).
5. E. Cady, L. Pueyo, R. Soummer, and N. J. Kasdin, "Performance of hybrid occulters using apodized pupil Lyot coronagraphy," Proc. SPIE **7010**, 70101X (2008).
6. C. J. Copi and G. D. Starkman, "The Big Occulting Steerable Satellite [BOSS]," Astrophys. J. **532**, 581–592 (2000).
7. W. Cash, "Detection of earth-like planets around nearby stars using a petal-shaped occulter," Nature **442**, 51–53 (2006).
8. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, 1996).
9. M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, 1999).
10. R. Soummer, L. Pueyo, A. Sivaramakrishnan, and R. J. Vanderbei, "Fast computation of Lyot-style coronagraph propagation," Opt. Express **15**(24), 15935–15951, (2007).

#168276 - $15.00 USD   Received 9 May 2012; revised 1 Jun 2012; accepted 5 Jun 2012; published 21 Jun 2012

2 July 2012 / Vol. 20, No. 14 / OPTICS EXPRESS 15196

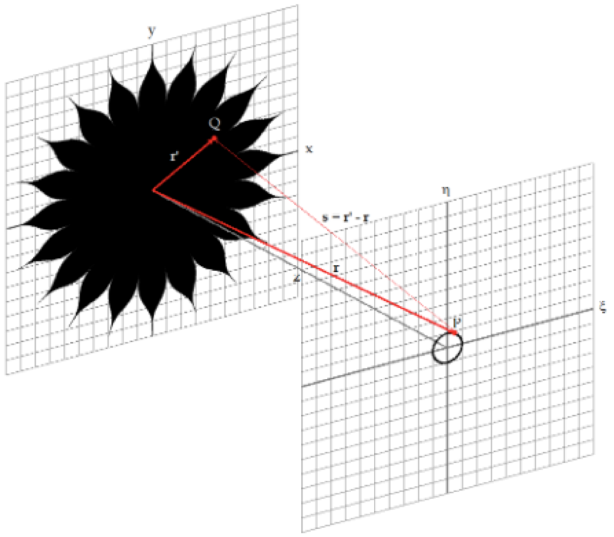
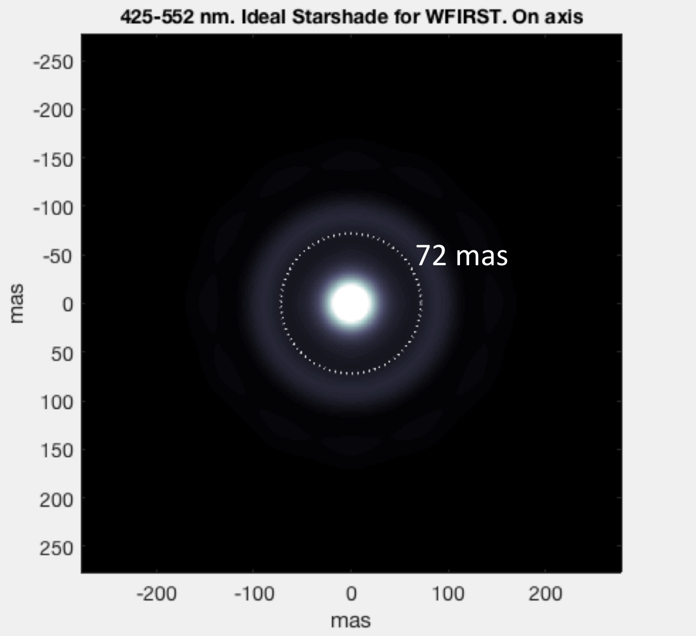


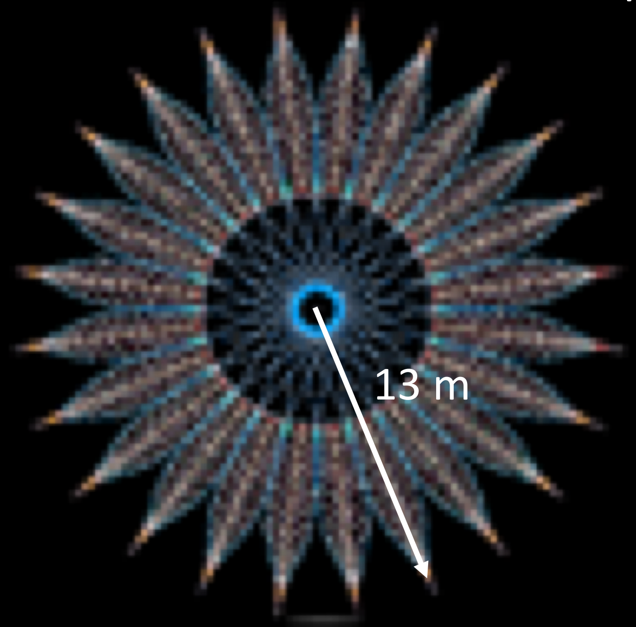
Fig. 2. A diagram of the points, coordinate systems, and vectors used in this paper. The left grid is in the plane of the occulter, and the right grid in the plane of the telescope aperture.

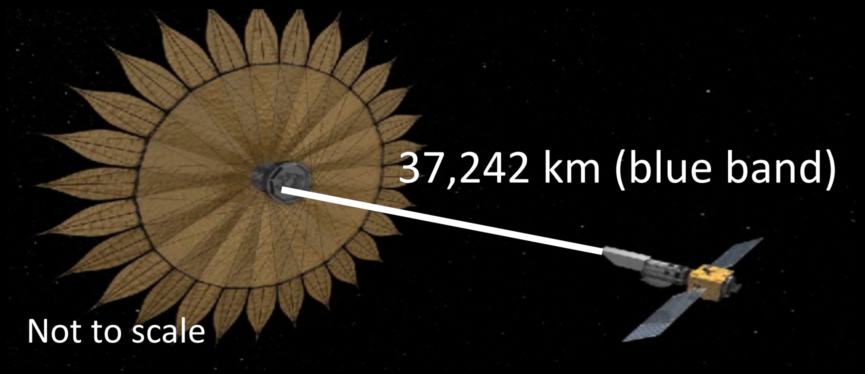


Eric's approach: the 2D structure of the occulter is reduced to a 1D edge integral using Stokes's theorem and a vector potential.

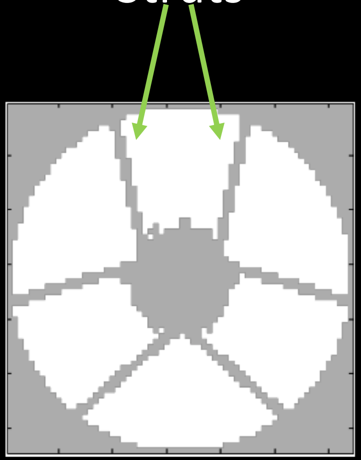
SISTER PSF Basis

Ideal WFIRST Starshade of 24 petals



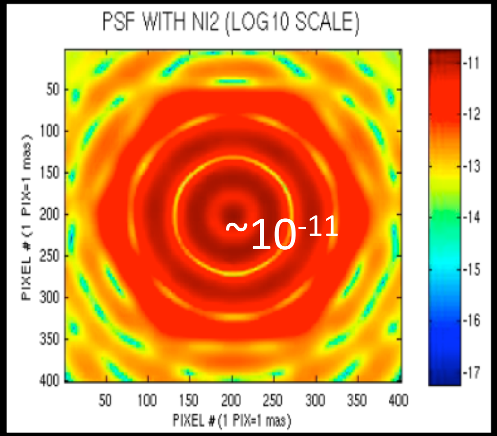


WFIRST Pupil
Struts

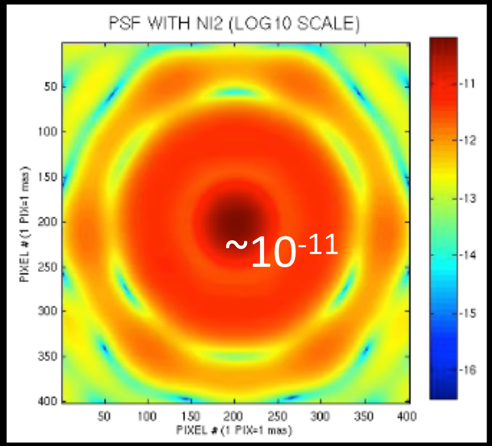


Relative intensity of the blocked star.
Non-spinning starshade

425 nm



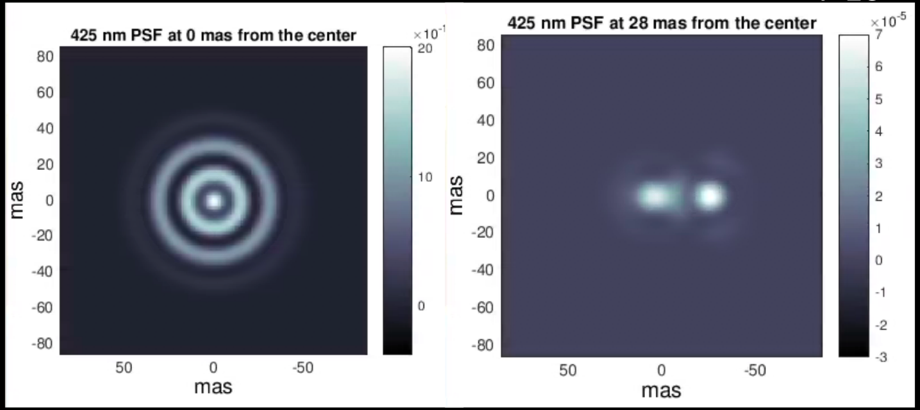
552 nm



SISTER PSF Basis

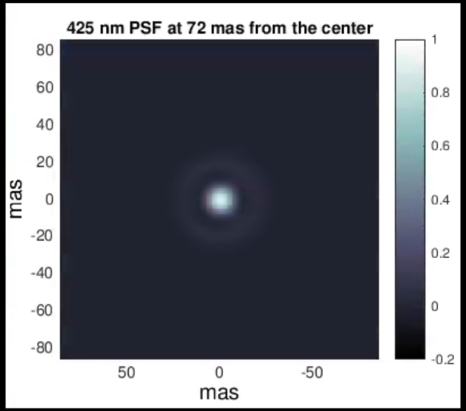
Point Spread Function (telescope response to a point-like source) at different distances from the center of the Starshade: 425-552 nm. Starshade-WFIRST distance of 37,200 km. Spinning starshade.

2 10^{-11} 7 10^{-5}



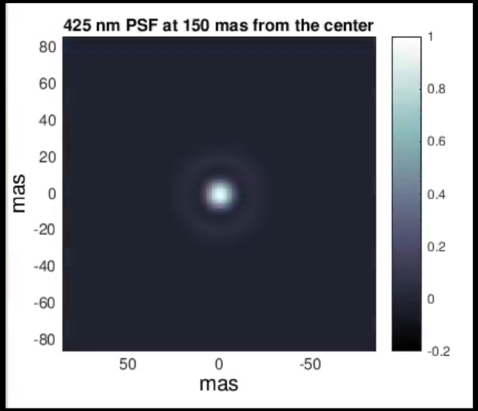
0 m, 0 mas 5 m, 27.7 mas

0.93

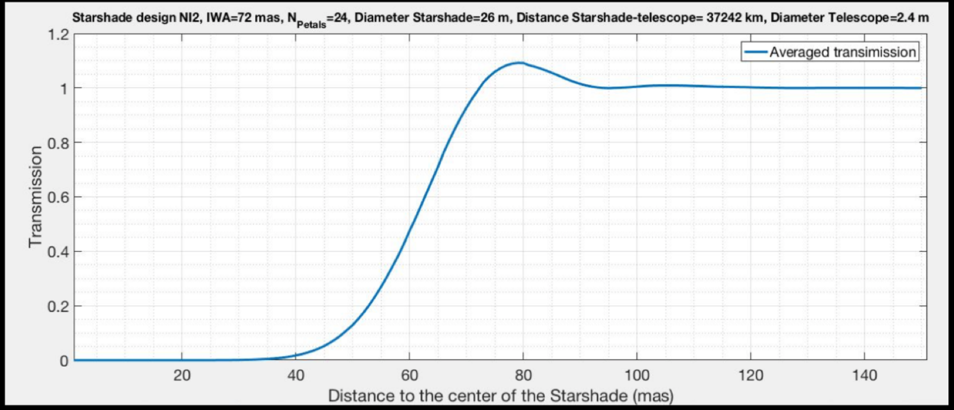


13 m, 72.0 mas

1.0



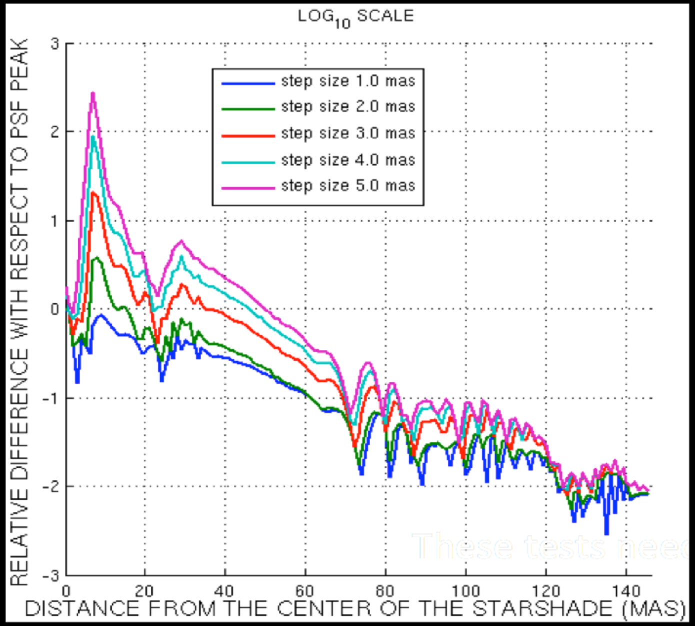
>= 150.0 mas

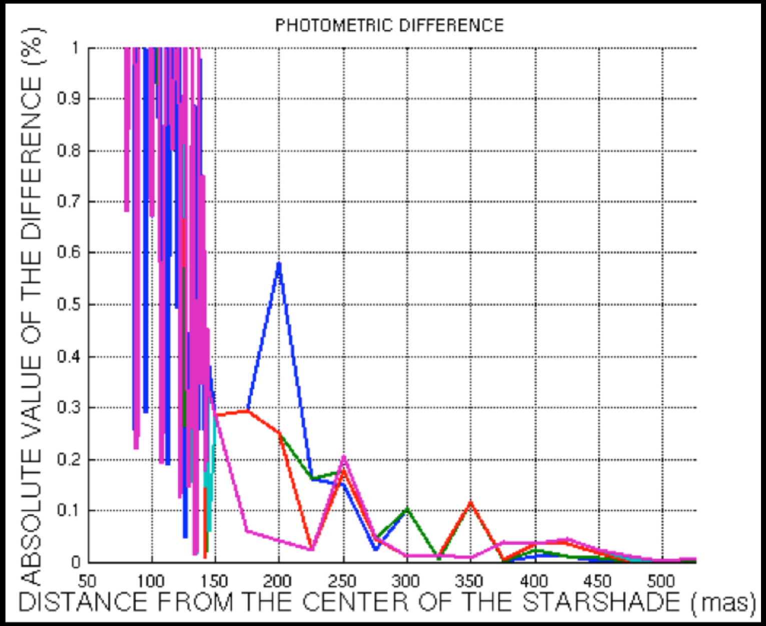


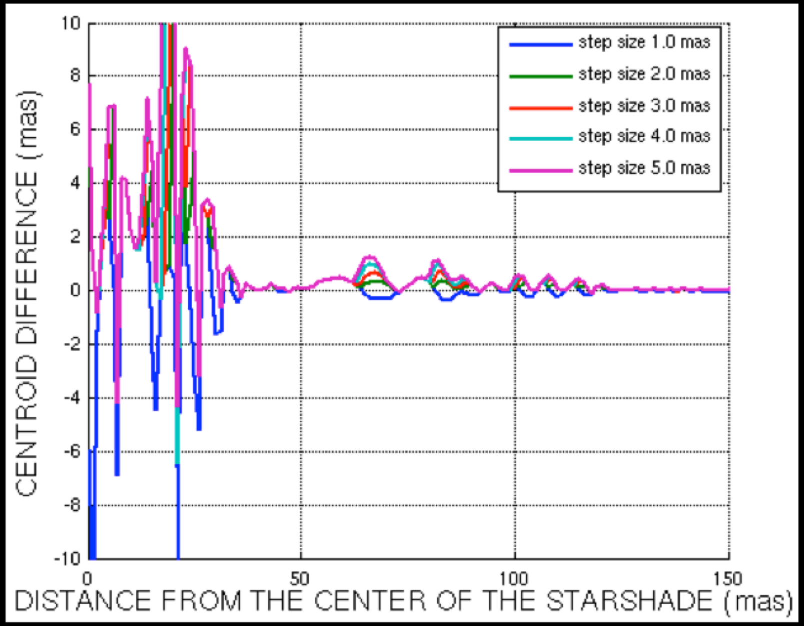
SISTER: Imaging Exoplanets with Starshade, 04/11/19 ExTWC

SISTER PSF Basis

The PSF basis consists of a library that depends on the spatial location on the image plane, pixel scale, and wavelength step*.
Example: testing precision with the spatial step on the image plane







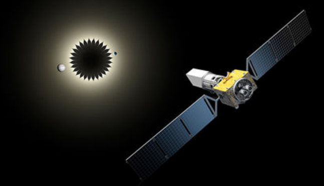
These tests need to be done for each starshade-telescope-filter combination

* S.R. Hildebrandt, S.B. Shaklan, E.J. Cady, and M.C. Turnbull (2019). In preparation.

SISTER Astrophysical and Instrumental Scenes

1. **Telescope:** primary, secondary mirror, pupil, optical efficiency, pointing jitter.
2. **Detector model:** read noise, dark current, Filters, QE. For WFIRST, a full EMCCD simulator* can be run externally to SISTER, including CIC, aging, and other effects.
3. **Starshade mode:** spinning, or non-spinning.
4. **Non-ideal Starshade:** shape deformations –very many.
5. **Solar glint:** target Star-Starshade-Sun angle, and Sun angle about the orbital plane. Different petal edges depending on the starshade mode: razor, stealth.
6. **Local Zodiacal light:** surface brightness model from STSCI, helio-centric coordinates.
7. **Star:** the user may define any star (its sub-spectral type will be approximated by either 0 or 5, e.g. G3 will be G5). Or one may choose among any of the 2,347 stars from ExoCat (M. Turnbull, 2015).

*EMCCD simulator developed by P. Morryssey, JPL.



SISTER Astrophysical and Instrumental Scenes

7. **Exo-dust emission:** any external model (for instance, from the Haystacks Project*). SISTER has as a proxy a very simple model scaled, rotated and resized from one run of Zodipic**.

8. **Planets and Keplerian orbits:** direct location, or 2-body motion with independent Keplerian parameters. No stability assessment.

9. **Reflected light from planets:** phase angle, phase functions (Lambert, Rayleigh).

10. **Extragalactic background:** deep field prepared by the Haystacks Project*.

11. **Proper motion and parallax:** given star coordinates and proper motion.

In progress:

1. Flight formation of the starshade (Flinois et al. 2019, S5 Milestone 4).
2. Stellar background (nearly finished).

* Haystacks Project A. Roberge, M. Rizzo et al. (2017).
** Zodipic by M. Kushner, GFSC.

SISTER Contributions
STARSHADE RENEDEZVOUS PROBE*

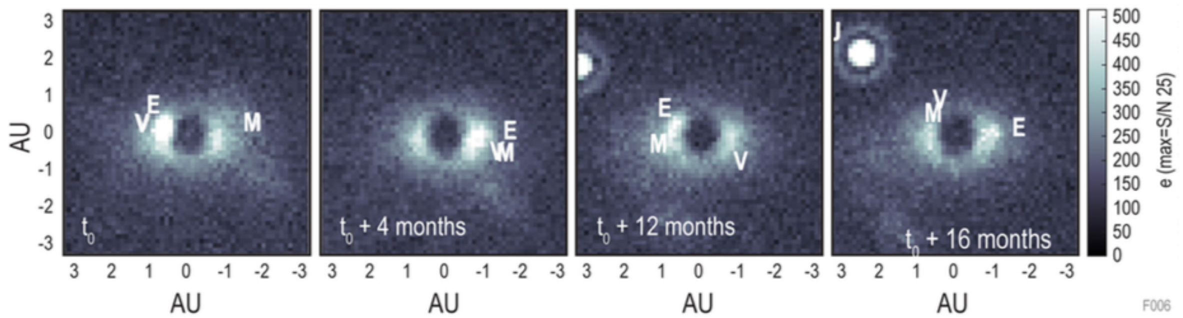


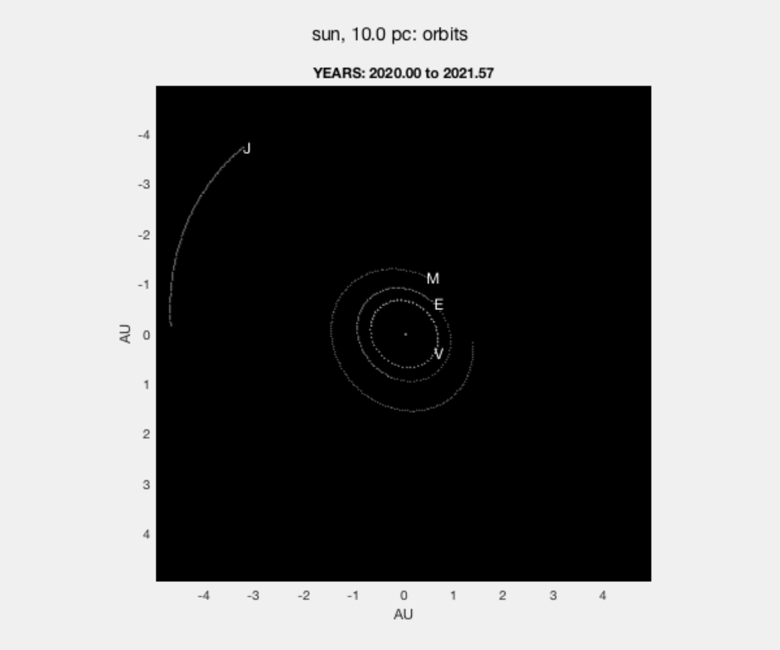
FIGURE 2-2. Multiple observations enable the tracking of habitable zone exoplanets. Image simulations of the solar system (inclination angle 60°) at a distance of 6 pc observed with a starshade and WFIRST CGI camera show the presence of Venus (V), Earth (E), and Mars (M) in a zodiacal dust cloud of 1 zodi. Jupiter (J) appears in the last two frames. Each image is obtained with 1 day of integration time. The color scale indicates the number of detector counts with the highest value being equivalent to signal to noise ratio of 25. Credit: Sergi Hildebrandt

***PI**: S. Seager, J. Kasdin (2019)
JPL POC: A. Romero-Wolf, A. Gray, J. Booth, S. Shaklan, D. Lisman, et al.

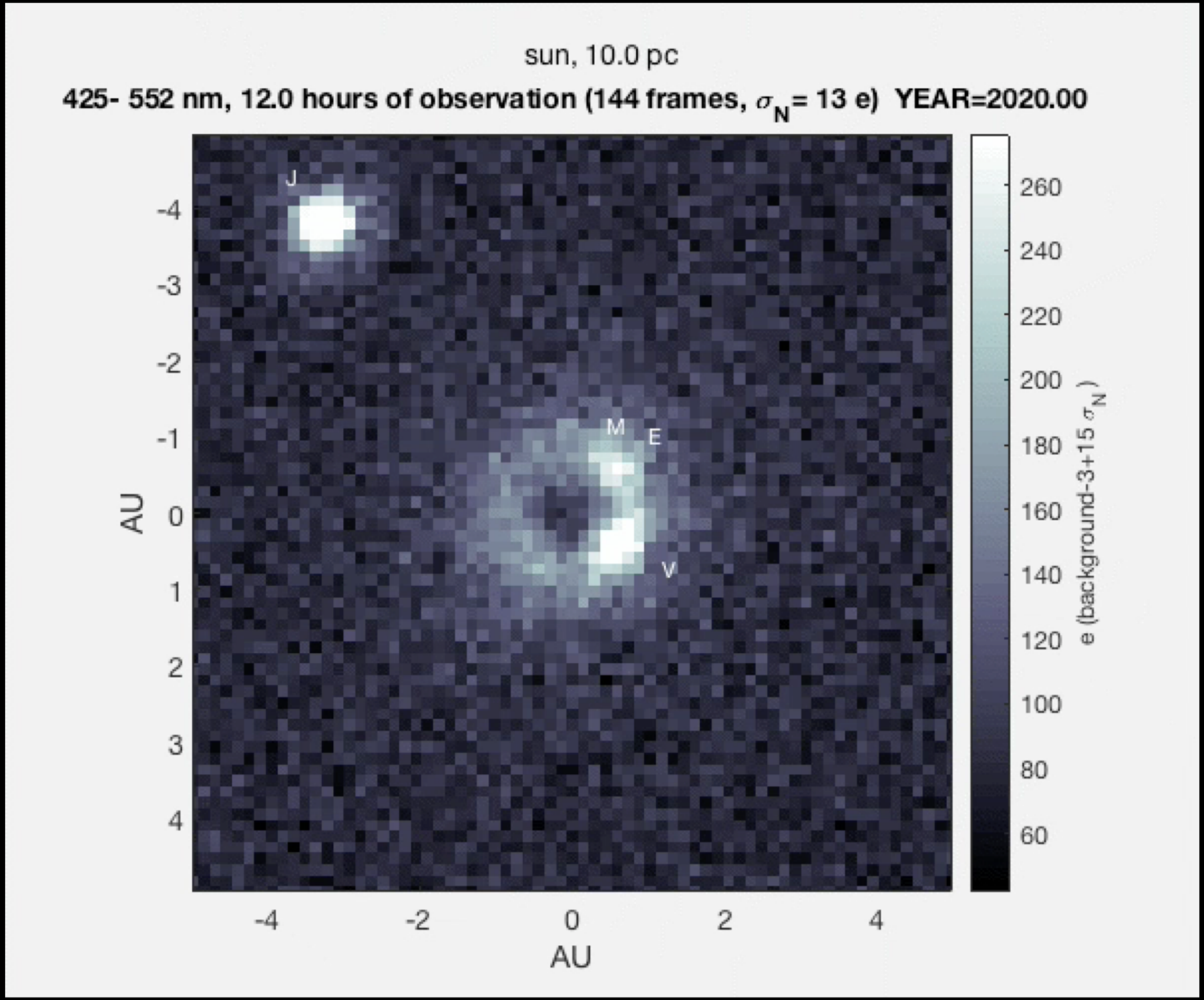
STARSHADE RENEDEZVOUS PROBE

Solar system at 10 pc, accurate EMCCD noise , QE detector and optical loses

SISTER

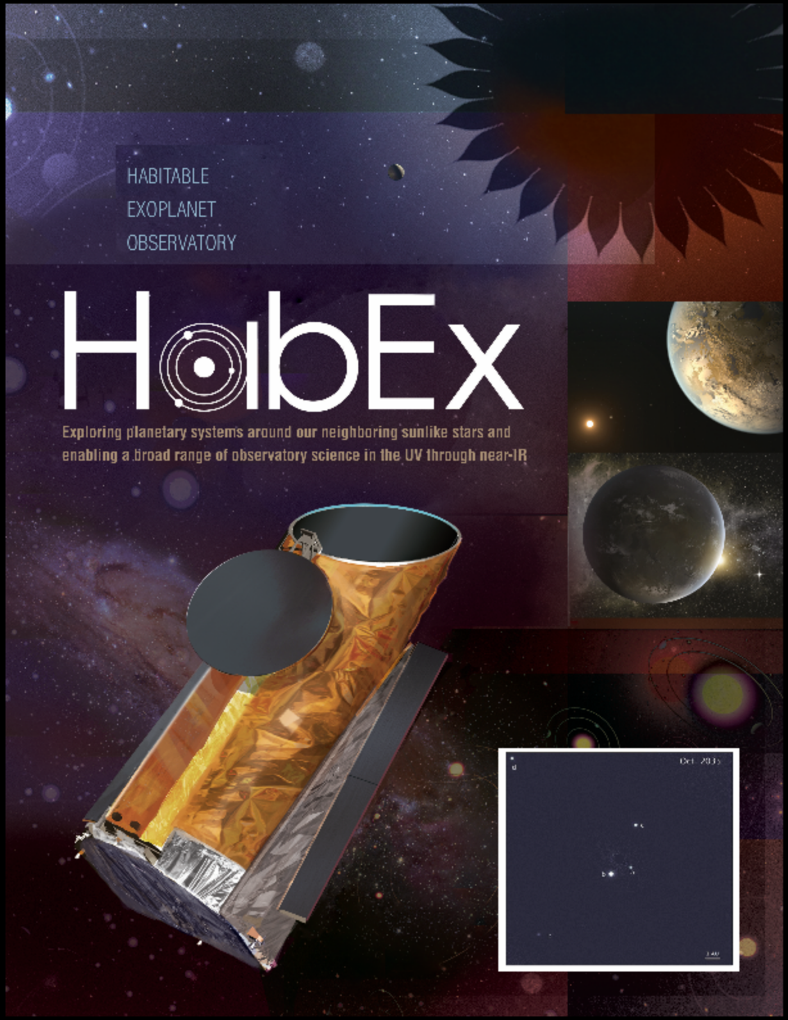


30º inclination and position angle of 45º



High signal to noise ratios

SISTER Contributions
HabEx*



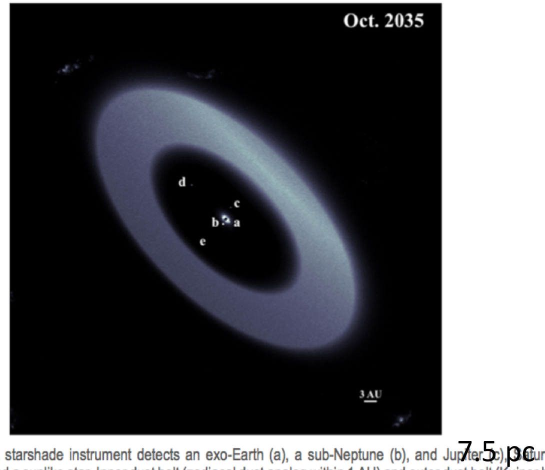


Figure 3.3-2. The HabEx starshade instrument detects an exo-Earth (a), a sub-Neptune (b), and Jupiter (c), Saturn (d), and Neptune (e) analogs around a sunlike star. Inner dust belt (zodiacal dust analog within 1 AU) and outer dust belt (Kuiper belt analog extending from 20 to 33 AU), both with three times the density of solar system level, are clearly visible together with some background galaxies. Same system as in Figure 3.3-1 but now with a field of view 11.9"×11.9" revealing the outer planets and dust belt. Credit: S. Hildebrandt.

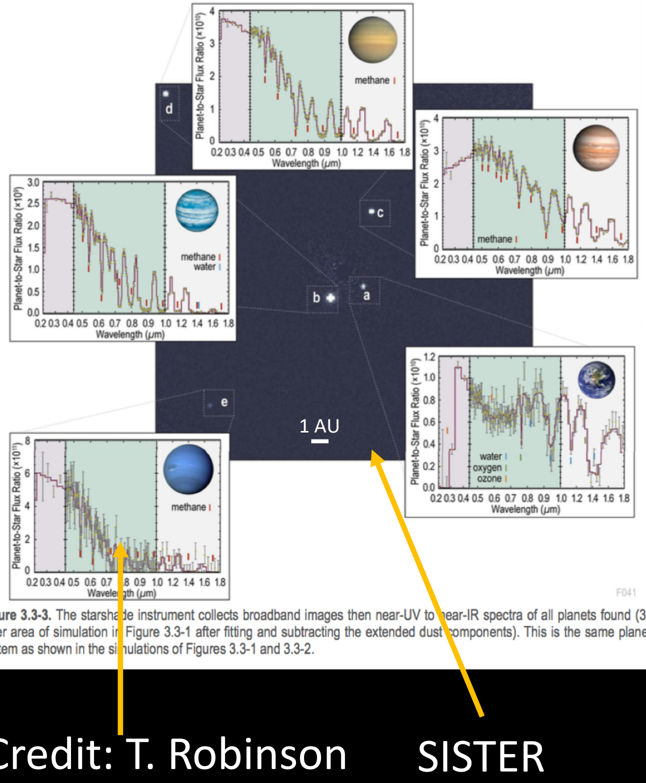
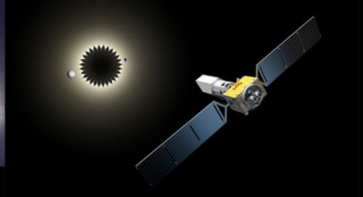


Figure 3.3-3. The starshade instrument collects broadband images then near-UV to near-IR spectra of all planets found (3"×3" inner area of simulation in Figure 3.3-1 after fitting and subtracting the extended dust components). This is the same planetary system as shown in the simulations of Figures 3.3-1 and 3.3-2.

***STDT** Chairs: S. Gaudi, S. Seager. **Study Scientist**: B. Mennesson.

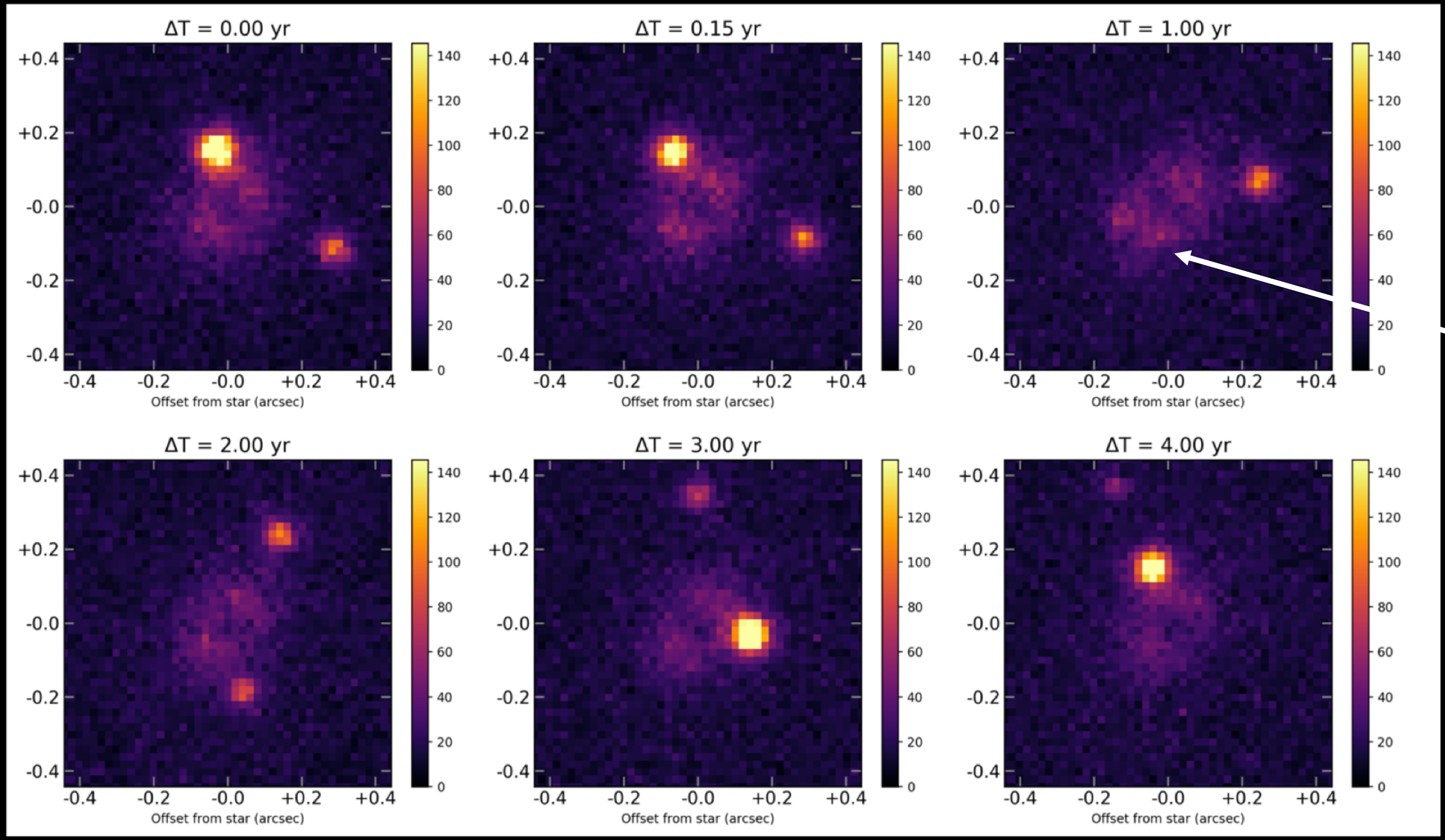


SISTER Contributions

WFIRST CGI DATA CHALLENGE*

47 Uma, 14 pc, planets b & c. Imaging + RV data. Orbital, albedo and planet discovery challenge.

4 first epochs will be replaced with CGI simulations. Last 2 epochs are with the starshade. Starshade images have several times higher signal to noise.

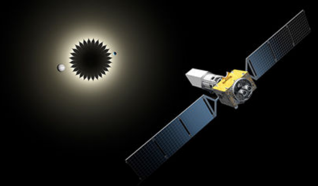


SS 6 hours of integration

Exozodi

1st Session at STSCI 03/18&19/19

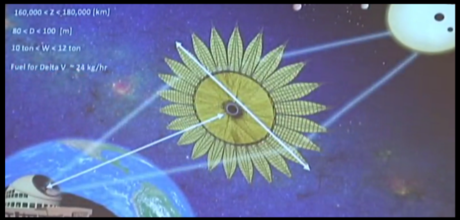
***PI:** M. Turnbull. turnbull.maggie@gmail.com, contact us to participate (next session at IPAC end of June 2019)

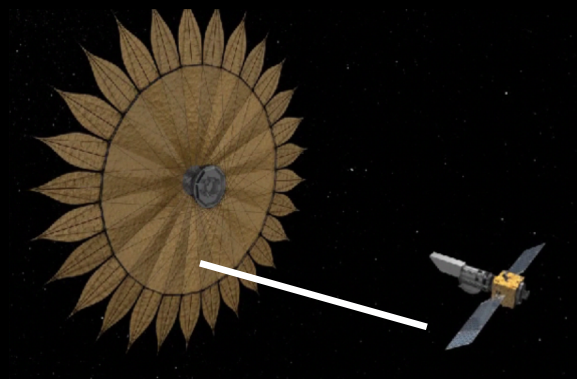


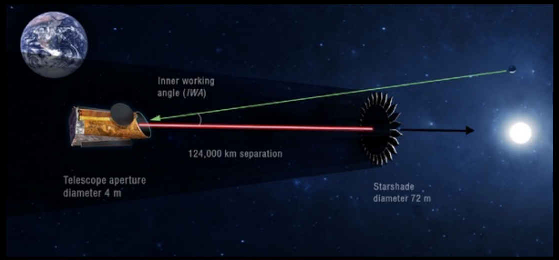
SISTER Next Steps

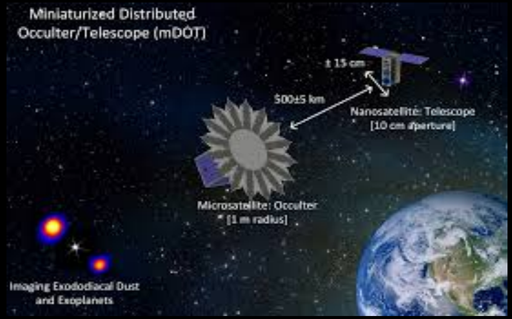
Besides adding the features mentioned before, SISTER may be helpful in order to:

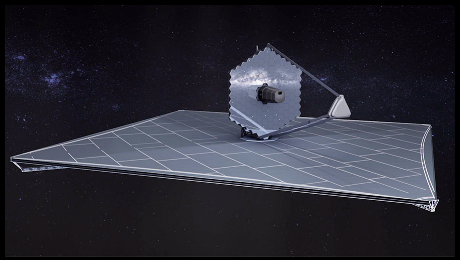
- Contribute to S5: Starshade Technology to TRL5: starshade perturbations, flight formation, solar glint.
- Support Mission Studies. In addition to WFIRST Rendezvous and HabEx: mDOT, Remote Occulter) and LUVOIR 8 m.
- Extend planet yield studies from Exposure Time Calculators to Actual Mission Simulations: EXOSIMS (R. Morgan/JPL , K. Cahoy/MIT).
- Launch Starshade Community Data Challenges.

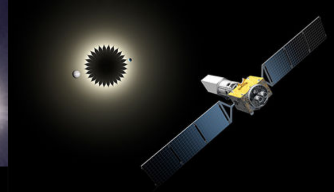












SISTER Public Release

sister.caltech.edu

Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)

Sergi R. Hildebrandt [1,a], Stuart B. Shaklan [1,b], Eric J. Cady [1,c], and Margaret C. Turnbull [2,1,d]

1: Jet Propulsion Laboratory/California Institute of Technology. 2: SETI Institute, Carl Sagan Center for Life in the Universe.

a: srh.jpl.caltech@gmail.com, b: stuart.b.shaklan@jpl.nasa.gov, c: eric.j.cady@jpl.nasa.gov, d: turnbull.maggie@gmail.com

The Starshade Imaging Simulations tool is a versatile tool designed to provide enough accuracy and variety when predicting how an exoplanet system would look like in an instrument that utilizes an Starshade to block the light from the host star: AAS233 Poster

The tool allows for controlling a set of parameters of the whole instrument that have to do with: (1) the Starshade design, (2) the exoplanetary system, (3) the optical system (telescope) and (4) the detector (camera). There is a built-in plotting software added, but the simulations may be stored on disk and be plotted with any other software.

The optical response of a starshade design is computed making use of the boundary diffraction wave method developed by Eric Cady (JPL/Caltech): SPIE, PDF

Sign-up SISTER Handbook SISTER Imaging Basis GitHub

SISTER Examples

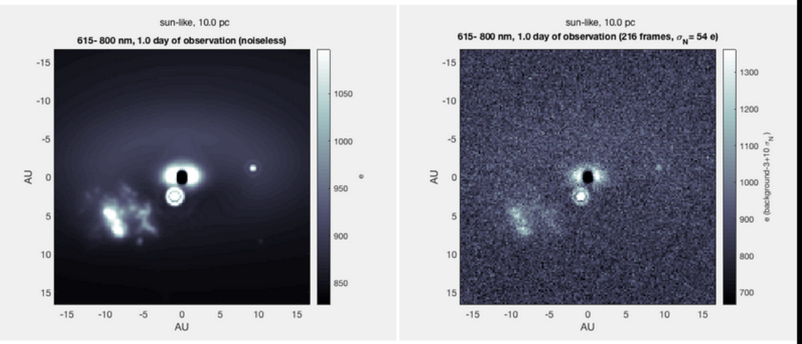


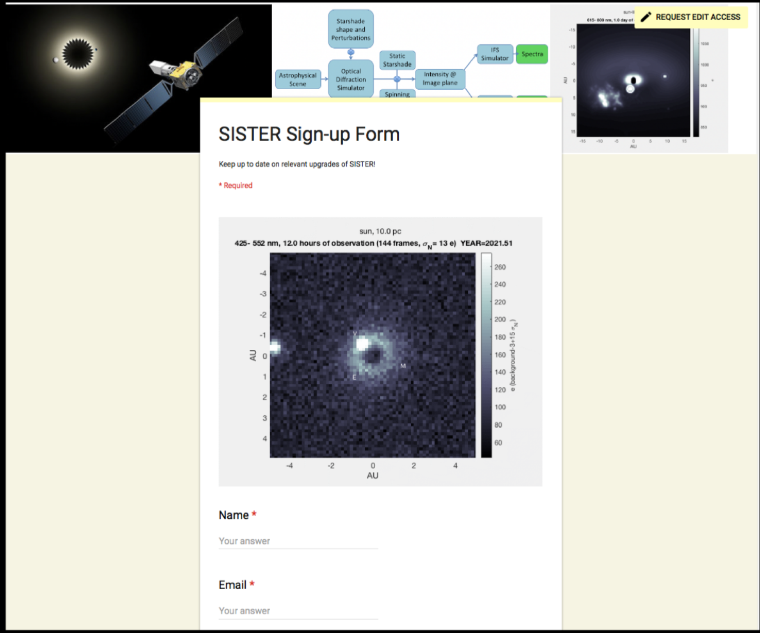
Figure 3.1: WFIRST RENDEZVOUS MISSION (GREEN BAND): Left: Noiseless simulation with SISTER of the solar system with some background objects at 10 pc and with an inclination of 60 degrees (Data from the Haystacks Project with local zodiacal light added). Right: Same as left, but including detector noise (standard CCD, not EMCCD) and shot noise. (see scene_5 in SISTER

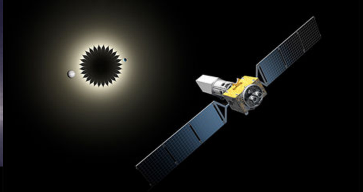
SISTER Handbook

Prepared by Sergi R. Hildebrandt[1] and Stuart B. Shaklan[2], JPL/Caltech

Table of Contents

[1] srh.jpl.caltech@gmail.com
[2] stuart.b.shaklan@jpl.nasa.gov





SISTER Public Release

sister.caltech.edu

Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)

Sergi R. Hildebrandt [1,a], Stuart B. Shaklan [1,b], Eric J. Cady [1,c], and Margaret C. Turnbull [2,1,d]

1: Jet Propulsion Laboratory/California Institute of Technology. **2**: SETI Institute, Carl Sagan Center for Life in the Universe.

a: srh.jpl.caltech@gmail.com, **b**: stuart.b.shaklan@jpl.nasa.gov, **c**: eric.j.cady@jpl.nasa.gov, **d**: turnbull.maggie@gmail.com

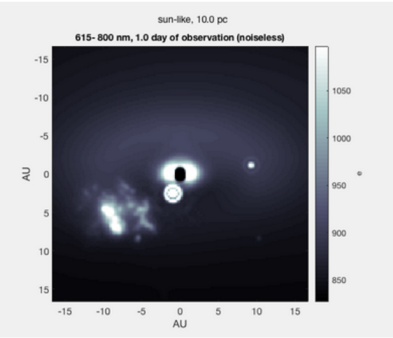
The Starshade Imaging Simulations tool is a versatile tool designed to provide enough accuracy and variety when predicting how an exoplanet system would look like in an instrument that utilizes an Starshade to block the light from the host star: AAS233 Poster

The tool allows for controlling a set of parameters of the whole instrument that have to do with: (1) the Starshade design, (2) the exoplanetary system, (3) the optical system (telescope) and (4) the detector (camera). There is a built-in plotting software added, but the simulations may be stored on disk and be plotted with any other software.

The optical response of a starshade design is computed making use of the boundary diffraction wave method developed by Eric Cady (JPL/Caltech): SPIE, PDF

Sign-up   SISTER Handbook   SISTER Imaging Basis   GitHub

SISTER Examples



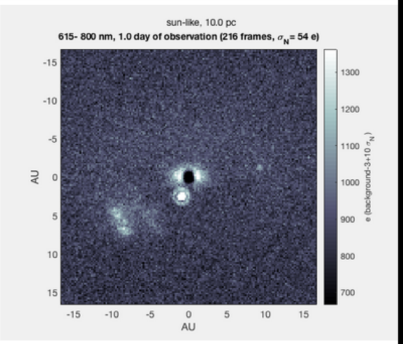


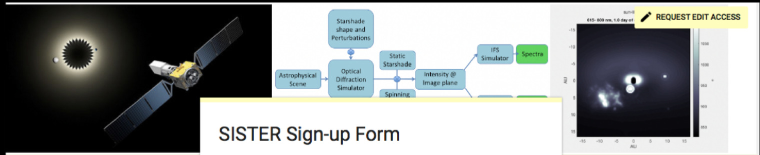
Figure 3.1: **WFIRST RENDEZVOUS MISSION (GREEN BAND): Left: Noiseless simulation with SISTER of the solar system with some background objects at 10 pc and with an inclination of 60 degrees (Data from the Haystacks Project with local zodiacal light added). Right: Same as left, but including detector noise (standard CCD, not EMCCD) and shot noise. (see scene_5 in SISTER**

SISTER Handbook

Prepared by Sergi R. Hildebrandt[1] and Stuart B. Shaklan[2], JPL/Caltech

Table of Contents

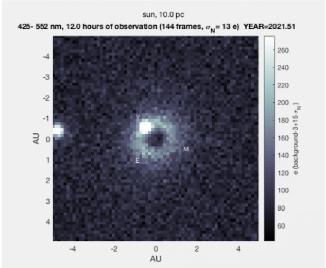
[1] srh.jpl.caltech@gmail.com
[2] stuart.b.shaklan@jpl.nasa.gov



SISTER Sign-up Form

Keep up to date on relevant upgrades of SISTER!

* Required



Name *
Your answer

Email *
Your answer

THANK YOU!