

Jet Propulsion Laboratory
California Institute of Technology

Starshade Imaging Simulations: Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)

Stuart Shaklan and Sergi Hildebrandt

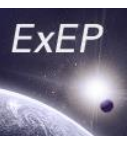
Jet Propulsion Laboratory

California Institute of Technology

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Overview



- Overview of capabilities
- How it works
- Accuracy analysis
- Examples of capabilities

What is SISTER?

SISTER is a Matlab-based, versatile tool designed to provide accurate, diverse starshade astrophysical simulations.

It allows for controlling a set of instrument and system parameters :

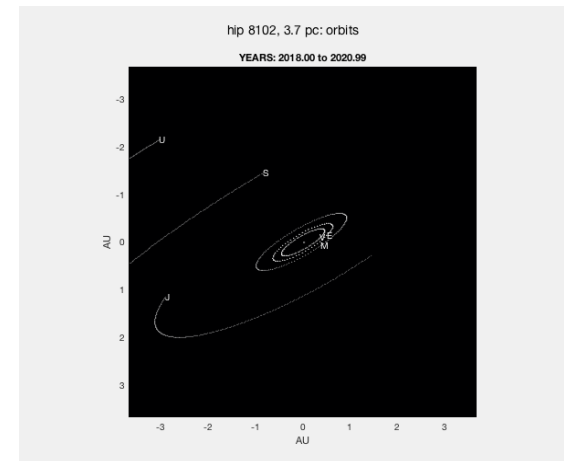
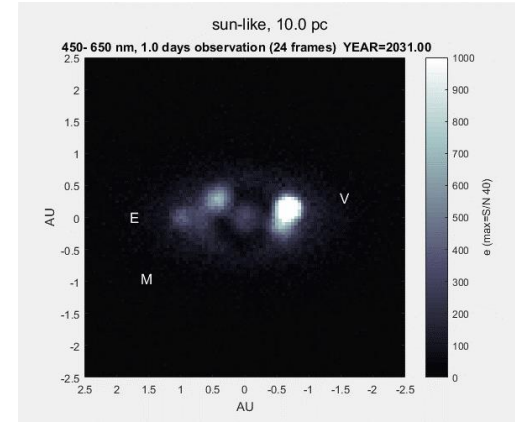
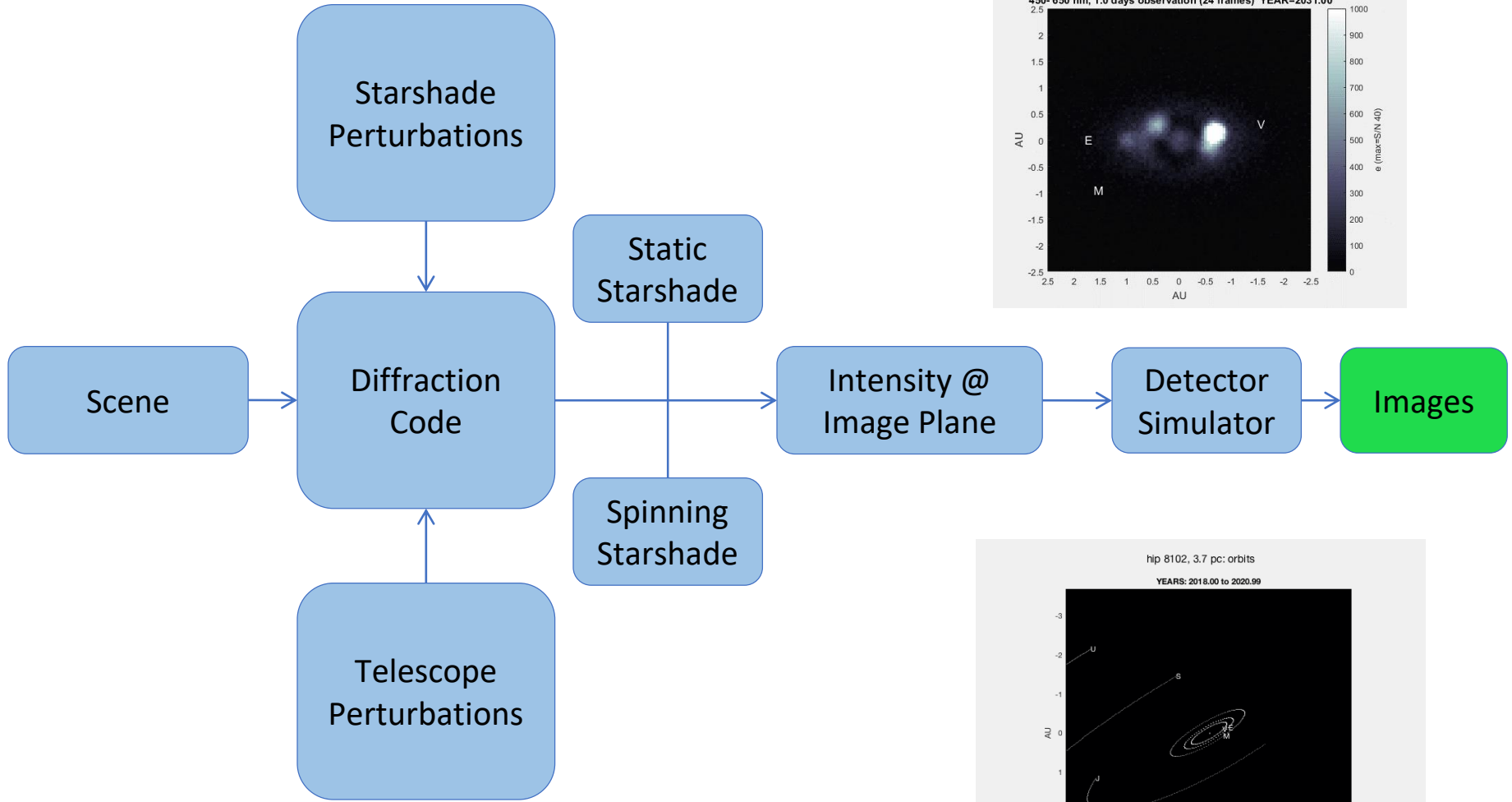
- (1) the starshade design and position,
- (2) the exoplanetary system,
- (3) the optical system (telescope) and
- (4) the detector (camera).

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, well-documented project that will evolve with starshade.

Sister.Caltech.edu

Starshade Optical Simulations



SISTER Instrument and Observational Parameters



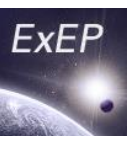
ExoPlanet Exploration Program

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.
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, chemically etched (Milestone 3 edges).
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](#)).

SISTER Instrument and Observational Parameters



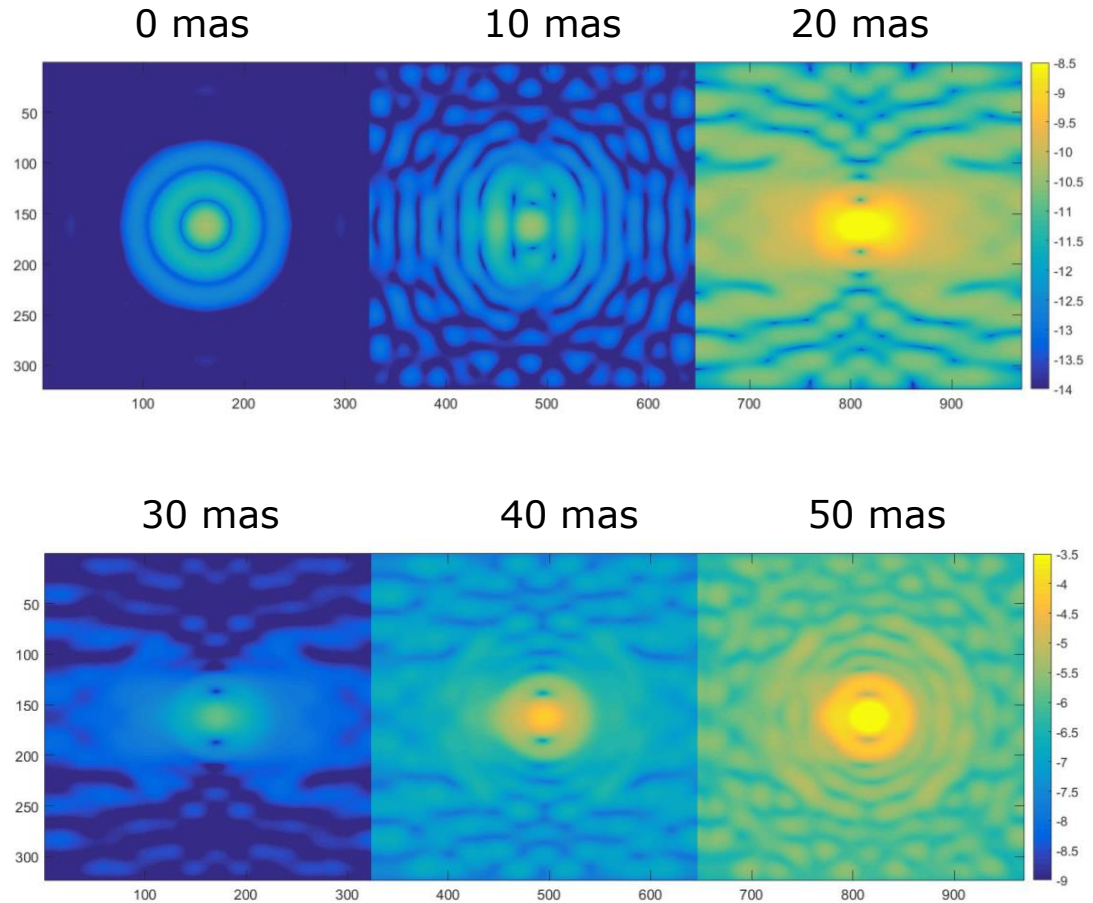
ExoPlanet Exploration Program

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.

PSF Basis Functions

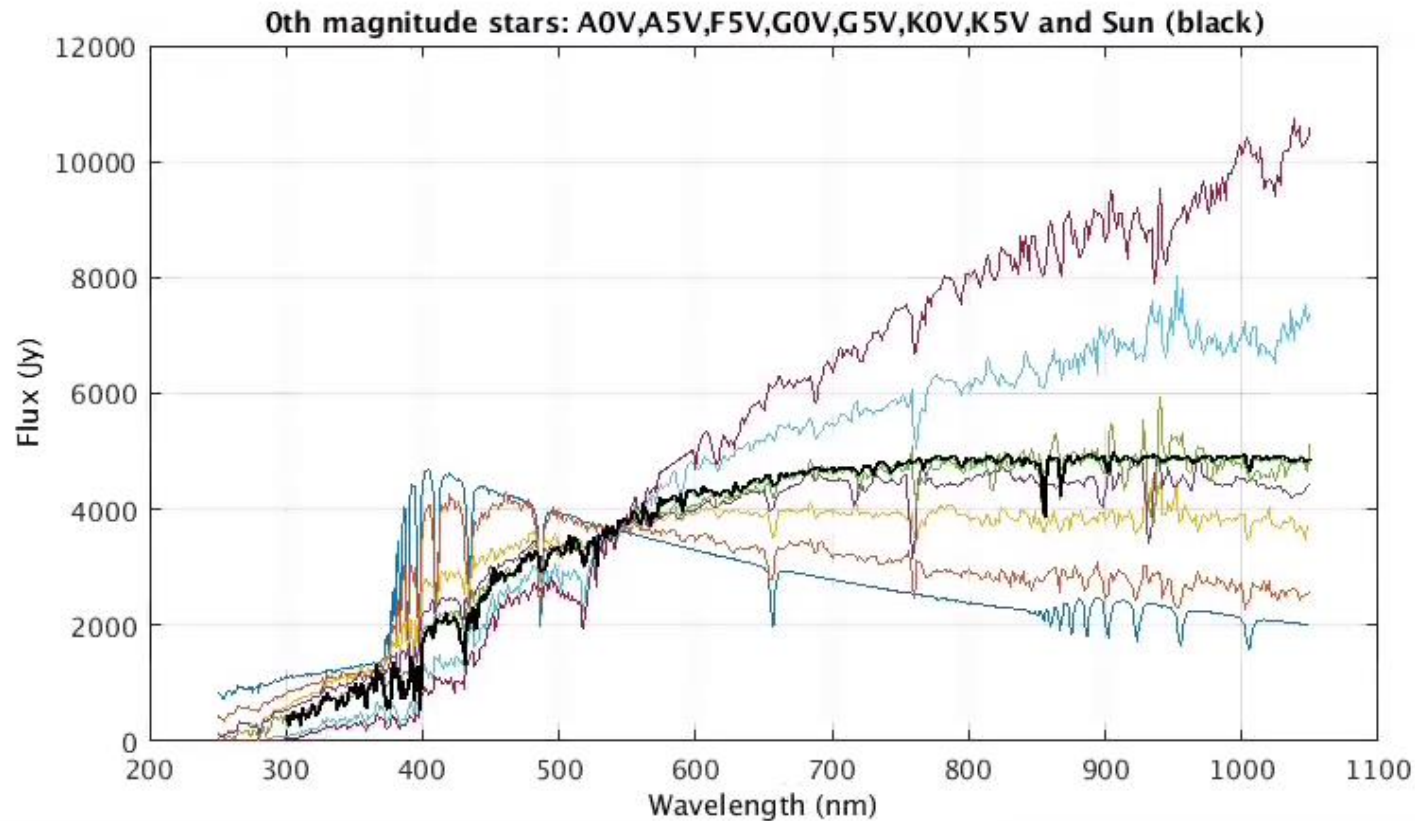
- For efficient operation, SISTER pre-computes basis functions:
 - For spinning starshades, PSF data cubes (x,y,wavelength) in 1 mas radial steps. Ignores primary mirror struts, and assumes the PSF has azimuthal symmetry.
 - For non-spinning starshades, generate pupil fields on the fly with a scene-dependent spacing. The fields are saved (typically 128x128 pixels) but the images are not – the file would be enormous.
- Precomputed basis functions for WFIRST SRM and HabEX (72 m and 52 m) are available at the SISTER website.

Example: SRM PSFs at 715 mas



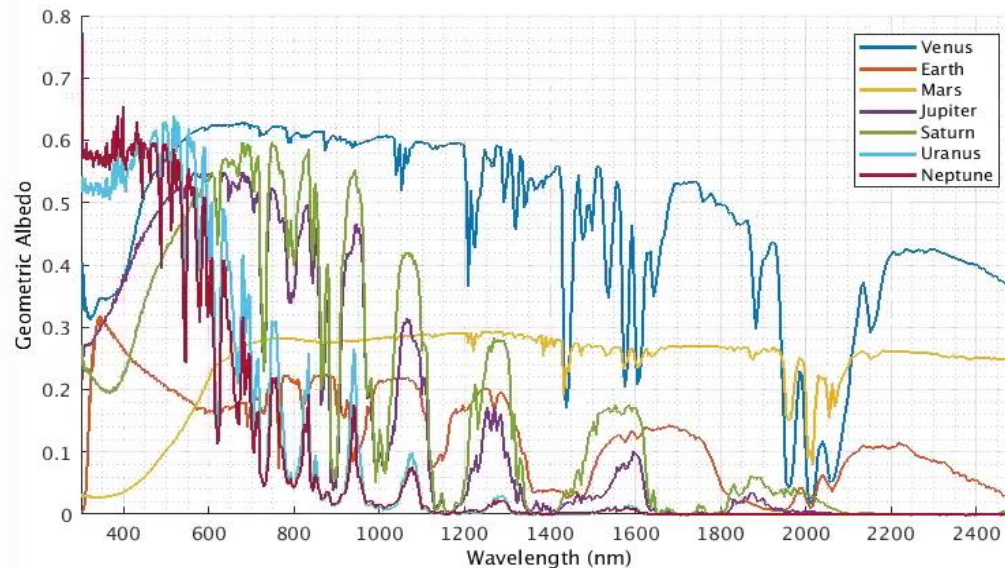
Stars

- Any star in ExoCAT can be selected, or stars can be defined by the user through a few simple parameters. Stellar spectra are represented to the nearest 0.5 spectral type.
- Spectra are integrated over the user-selected imaging band.
- SISTER reads Parallax and Proper Motion from ExoCAT, or user can enter it.



Planets

- User can specify a planet in static position or a Keplerian orbit.
- User can specify planet characteristics (r, albedo) or choose a solar-system planet with a spectrum from Haystacks

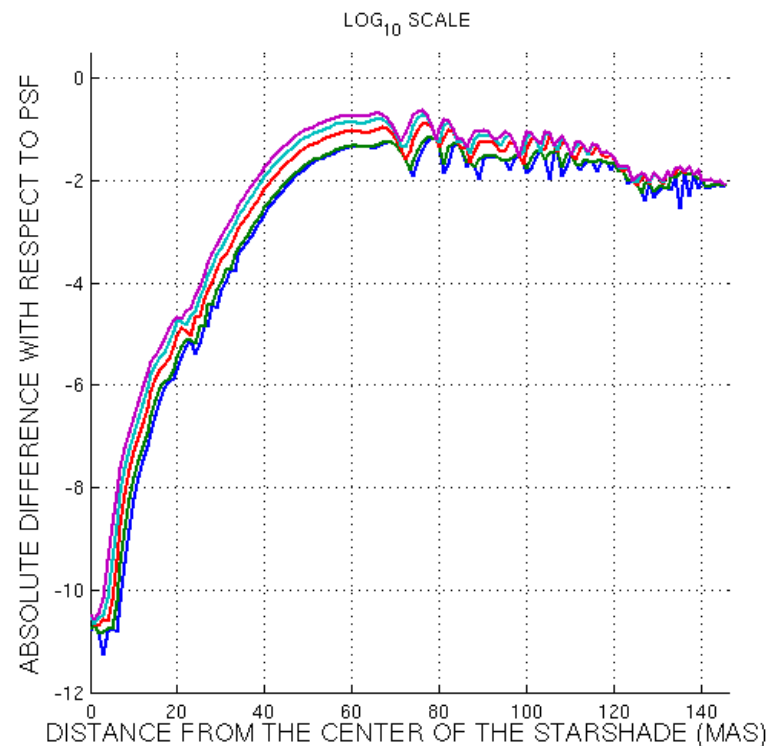
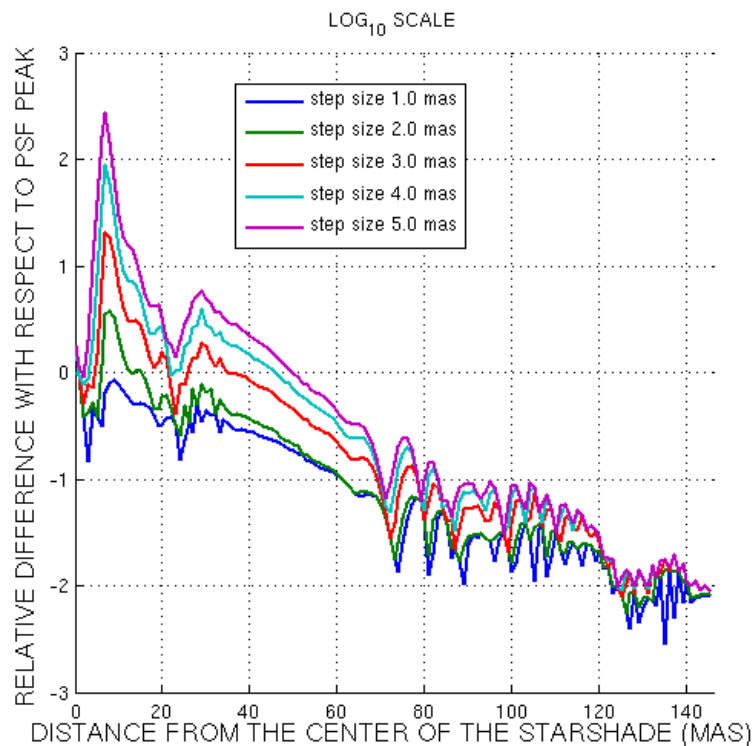


- There are no orbital stability checks in SISTER
- Choose from Lambertian or Rayleigh phase function, or specify the phase.

PSF Basis Function: Sampling Density

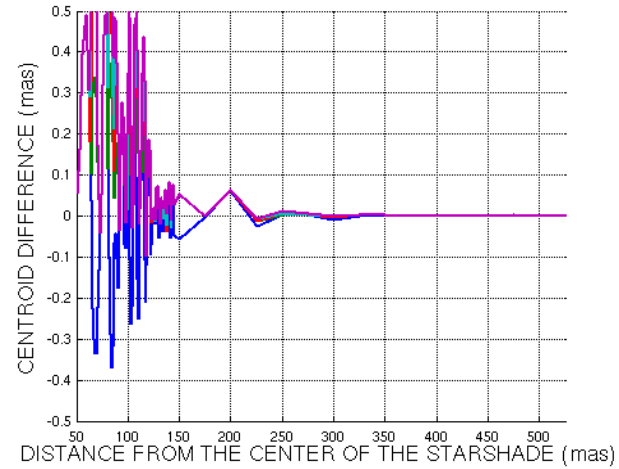
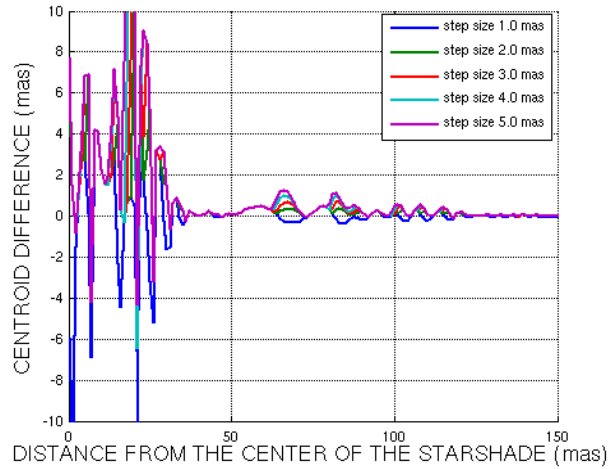
- How accurate is the PSF if interpolated between a coarsely sampled basis function?
- For 5 mas spacing, the peak of the PSF shows 10% errors when interpolating between PSFs. (WFIRST SRM example at 425 nm).
- For extended sources such as exo-Zodi, a 5 mas spacing results in $< 1\%$

ANALYSIS OF THE PSF STEP SIZE FOR POINT-LIKE SIGNAL

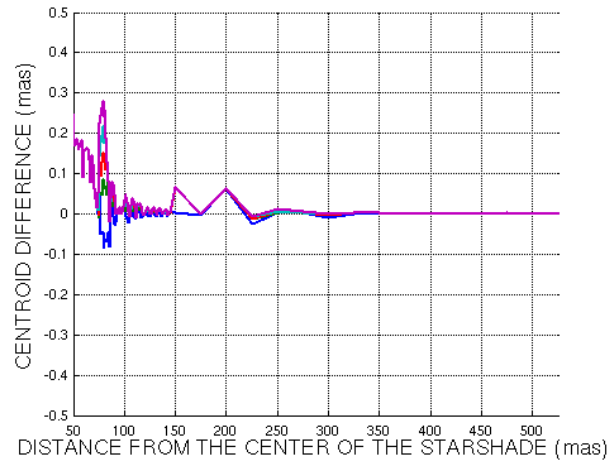
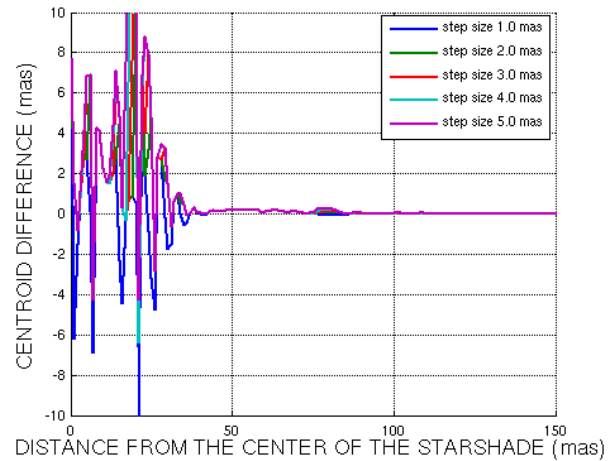


PSF Basis Function: Astrometric Error

NON-ROTATING STARSHADE



ROTATING STARSHADE

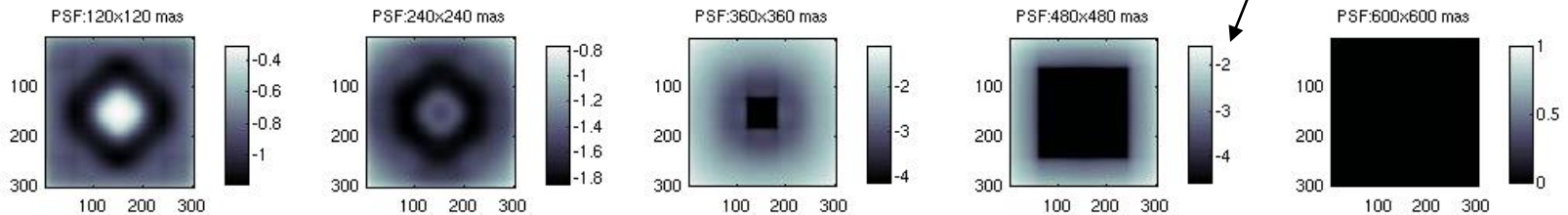


PSF Basis Function: How extended?

- The PSF rings down after a few Airy rings. How many rings are enough?
- We tested the accuracy of a face-on and inclined Exo-Zodi image for different PSF extensions, and found that 7 lambda/D was adequate for 1% reconstruction.

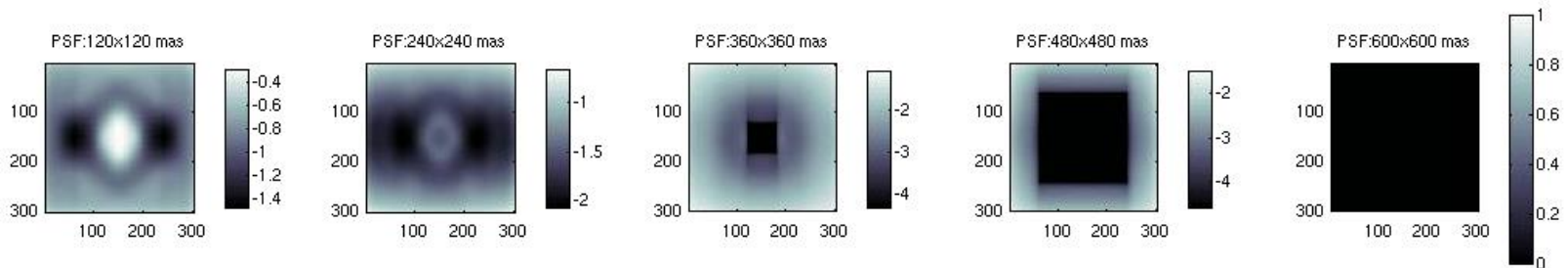
PSF @ 425 nm, FWHM = 36 mas, 1 PIX = 1 mas

Face on



Log ratio

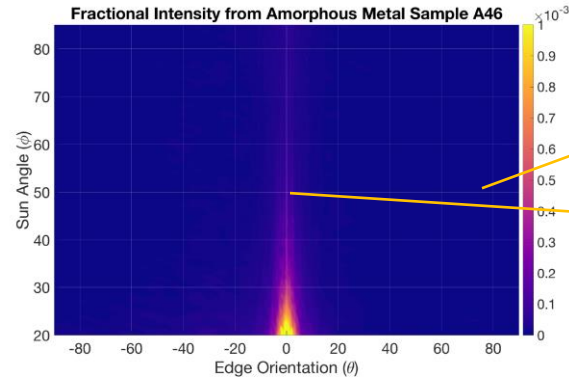
Inclined 60°



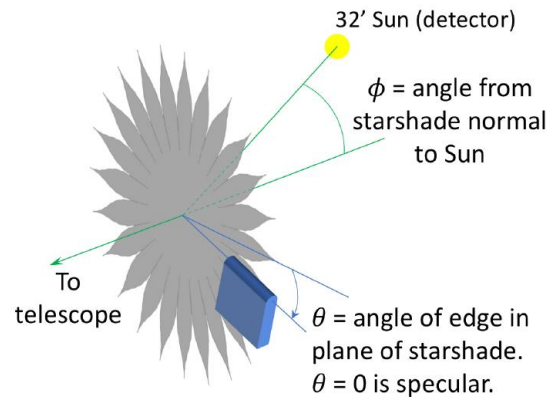
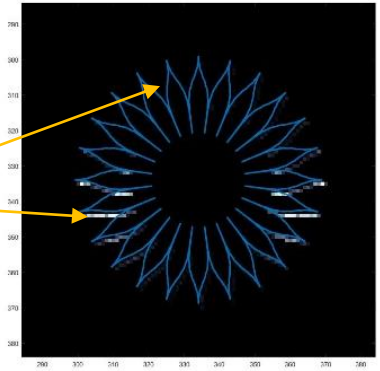
Solar Glint Calculations

- SISTER reads the starshade petal locus file, determines orientation of edges relative to the Sun.
- Reads the laboratory scatter map (a sort of BRDF for the starshade edge) and picks out the cell matching each edge locus orientation, scaling the cell for the distance of the starshade, the length of the segment, and the wavelength.
- Multiplies by the solar spectrum.
- Convolves the pattern with the telescope PSF.
- Calibration was performed using a m long edge segment and a heat map generated from an ideal half-plane analytical model (diffraction only).
- Comparison between the SISTER imaging result and a spreadsheet prediction using the analytical model was consistent to 0.05 mag (5%).

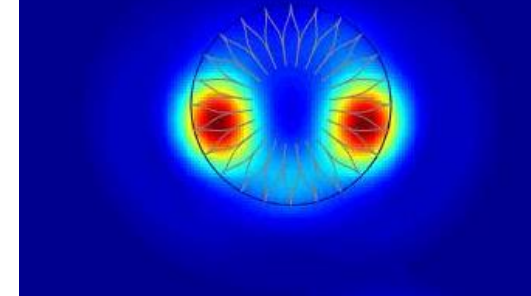
Scatter map



High-Res scatter pattern



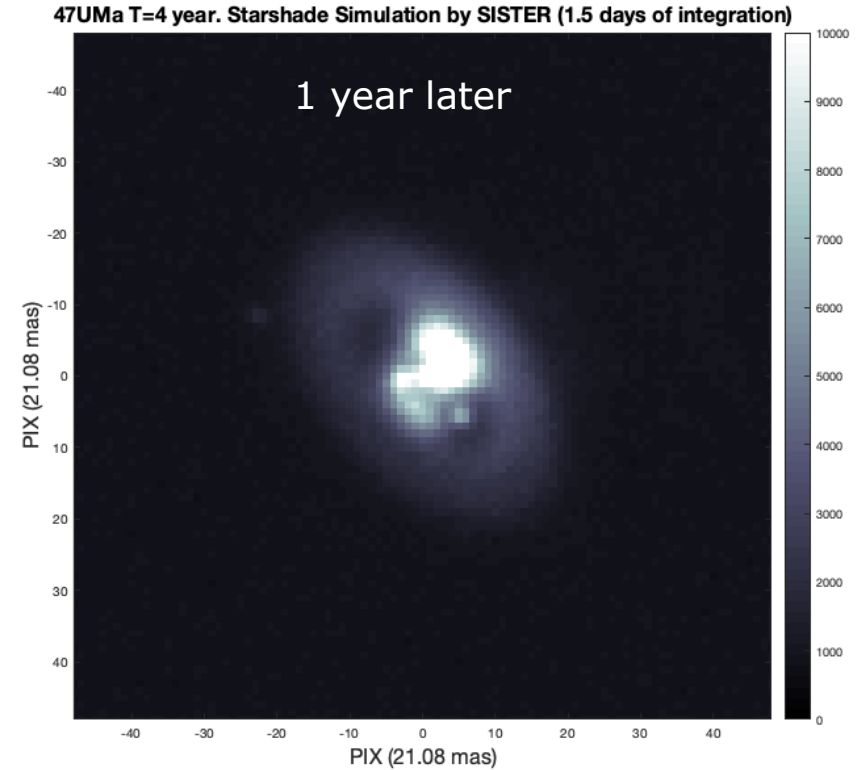
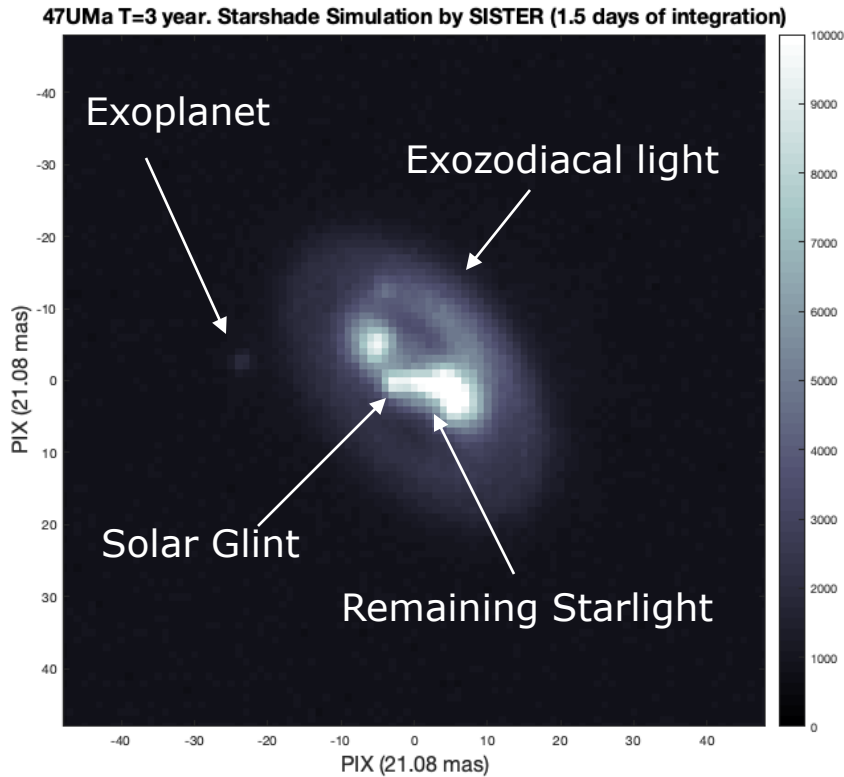
After convolving with telescope PSF.



Simulation for SRM Data Challenge: Planets and Exozodi around 47UMa



ExoPlanet Exploration Program



WFIRST CGI

Home Timeline & Data Tutorial Events Links

WFIRST Exoplanet Imaging Data Challenge

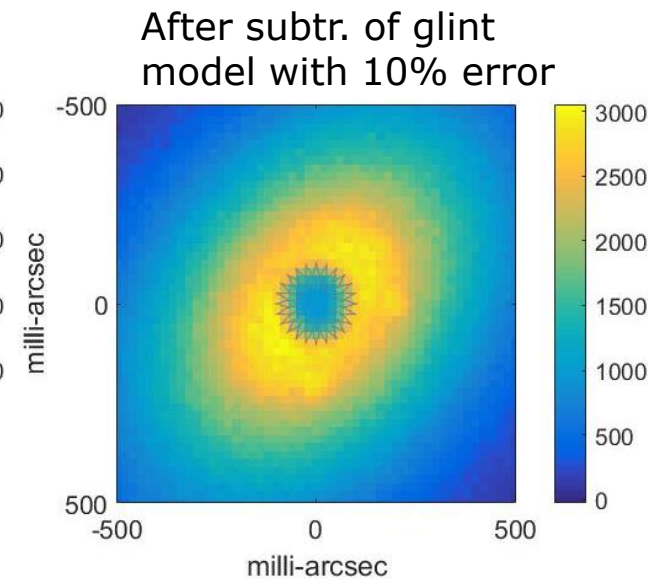
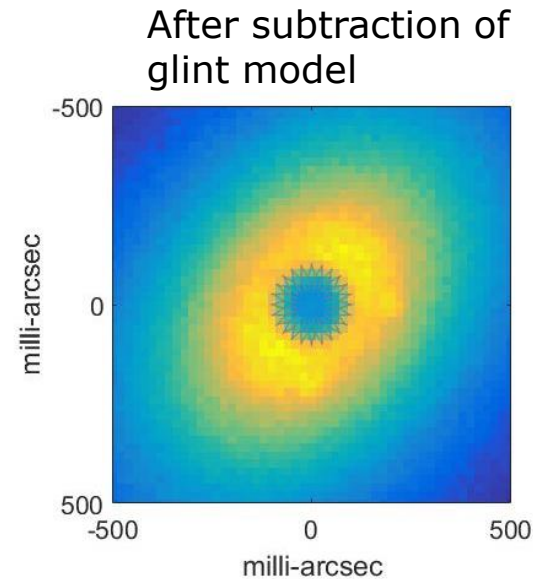
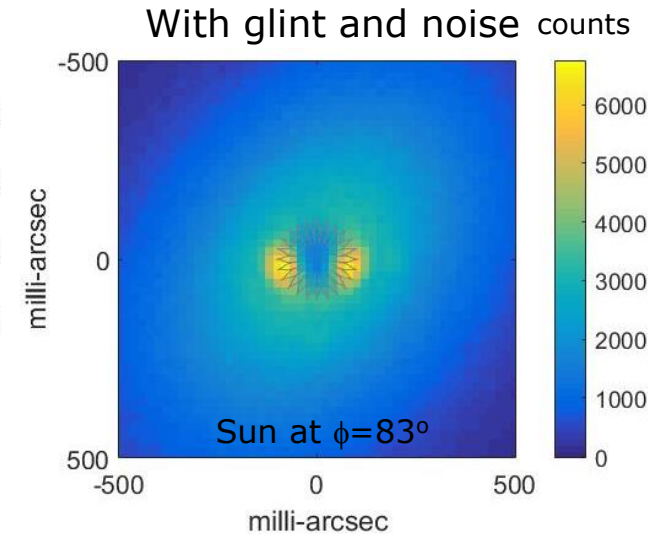
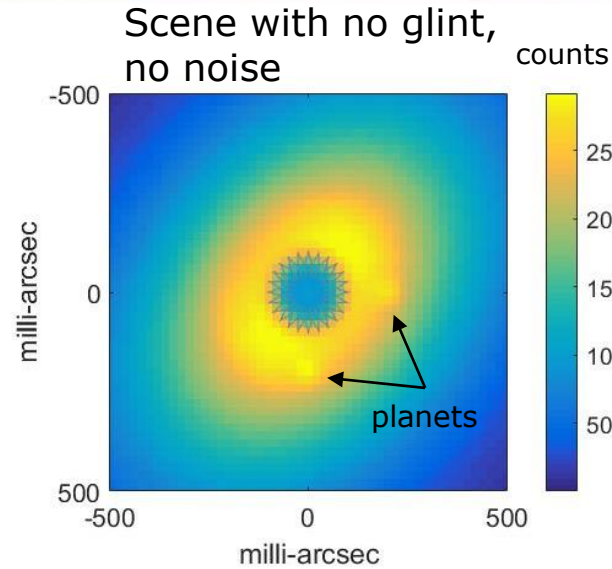
Core Team: Turnbull (PI), Zimmerman, Girard, Gonzalez, Hildebrandt

SRM Performance Assessment Example (Earth-like planets around Tau Ceti)



ExoPlanet Exploration Program

- $V=3.49$, Dist = 3.65, $L=0.52L_{\text{sun}}$
 - EEID = 197 mas.
 - Earth at quadrature would be $1.92e-10$ contrast. $V=28$.
- Exozodi density = 4, inclined 46.5 deg, P.A. = 52 deg.
- Observing band 620-800 nm.
- 1 day exposure, throughput = 0.1, shot noise and dark current only, 20 mas pixels.
- For SRM, the glint lobes are bright but their shot noise is not prohibitively large.
- In this example, the accuracy of the subtraction is not critical, but in some cases the requirement could be <10% glint lobe estimation error.



Remote Occulter Imaging a Solar System at 17 pc

Solar type star, V=6

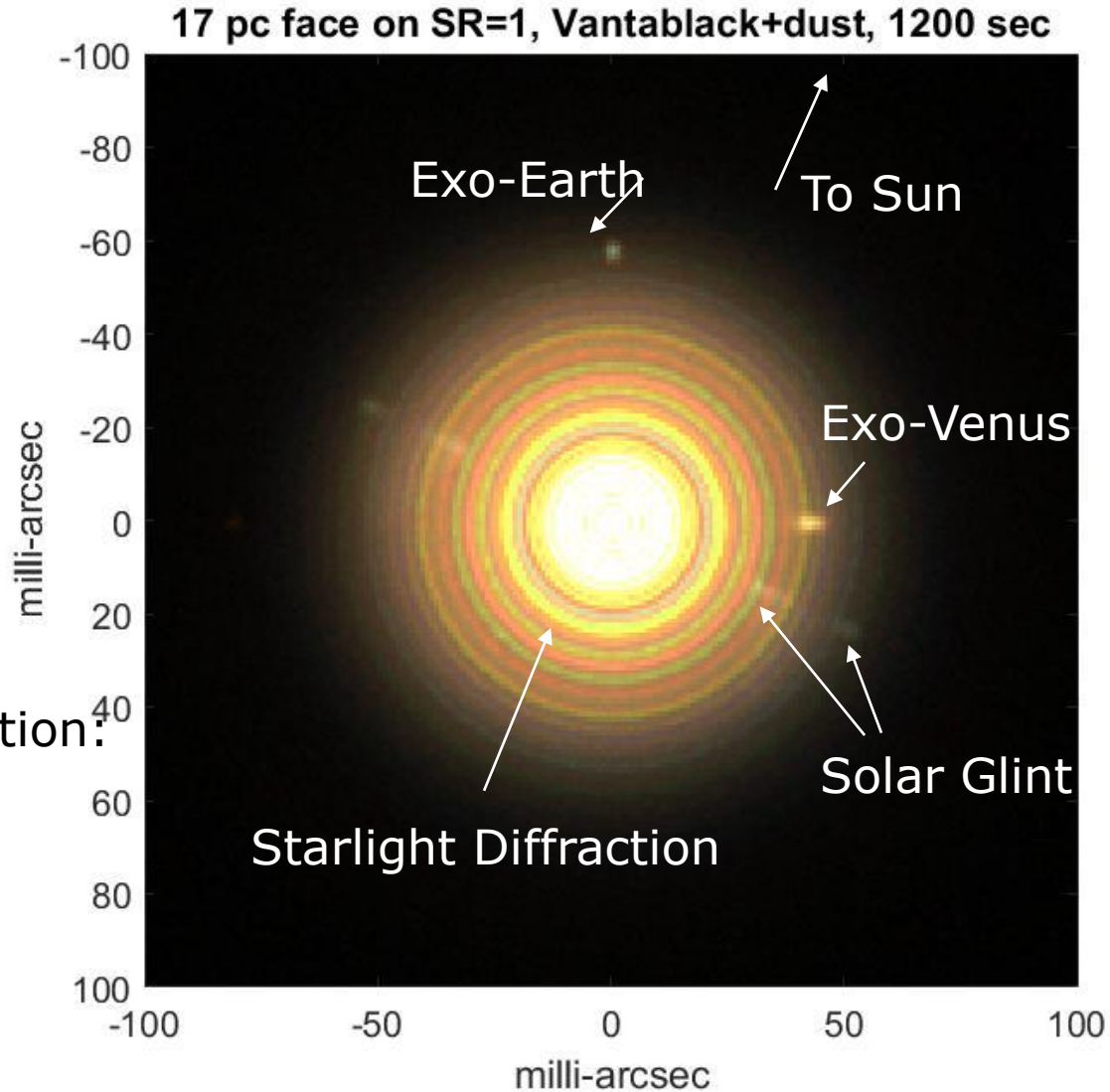


ExoPlanet Exploration Program

100 m telescope with 39 m aperture (no turbulence)

Three Bands:
400-500 nm
500-600 nm
600-700 nm

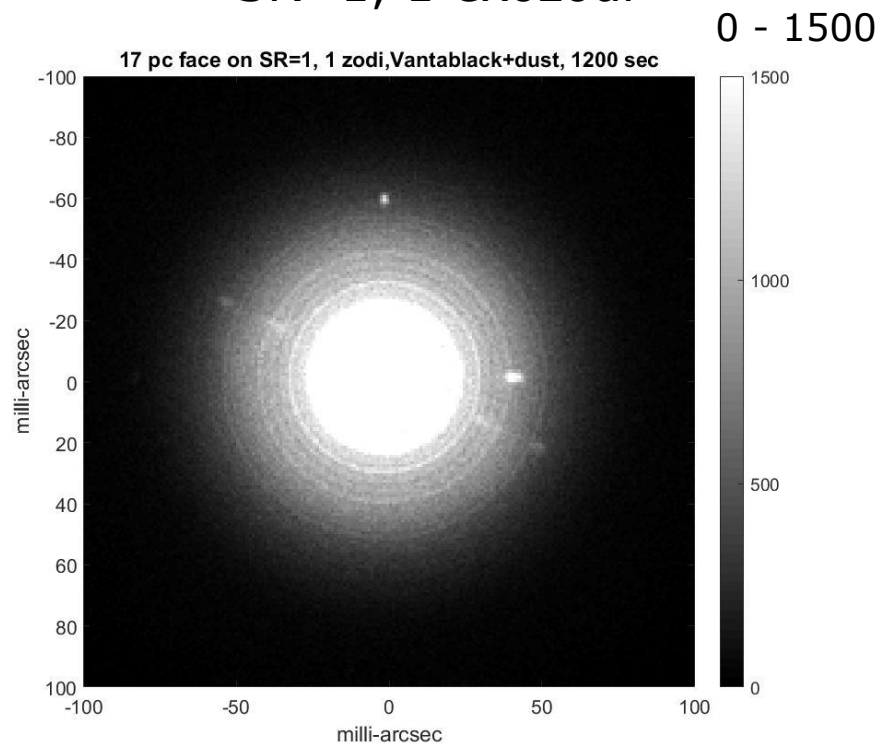
Starlight Diffraction:
Peak 8×10^{-9}
Total 7×10^{-8}



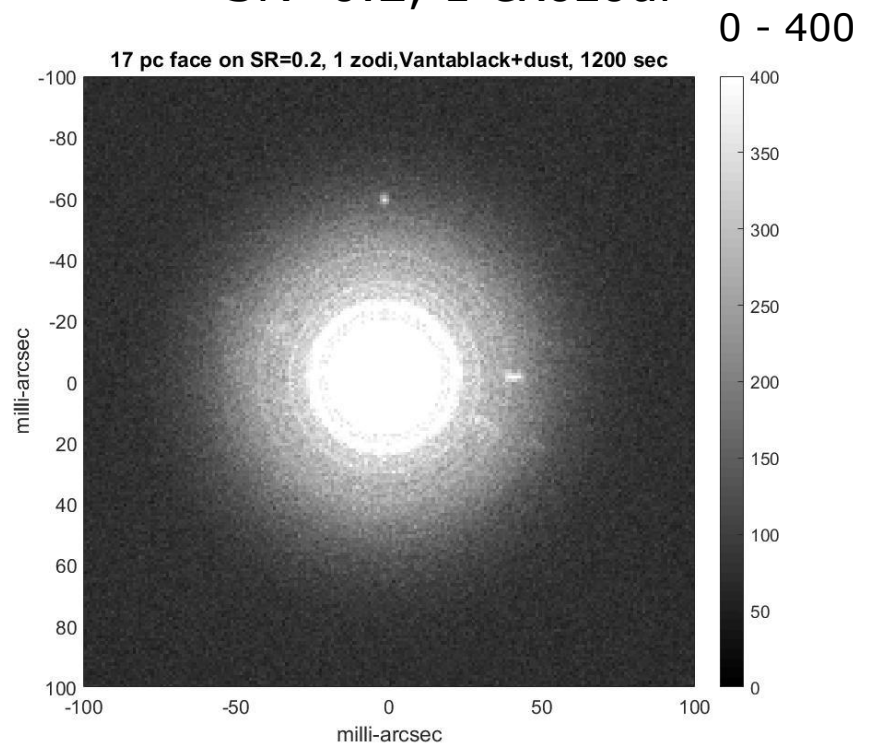
Remote Occulter Imaging at Strehl Ratio = 1.0 and 0.2



SR=1, 1 exozodi



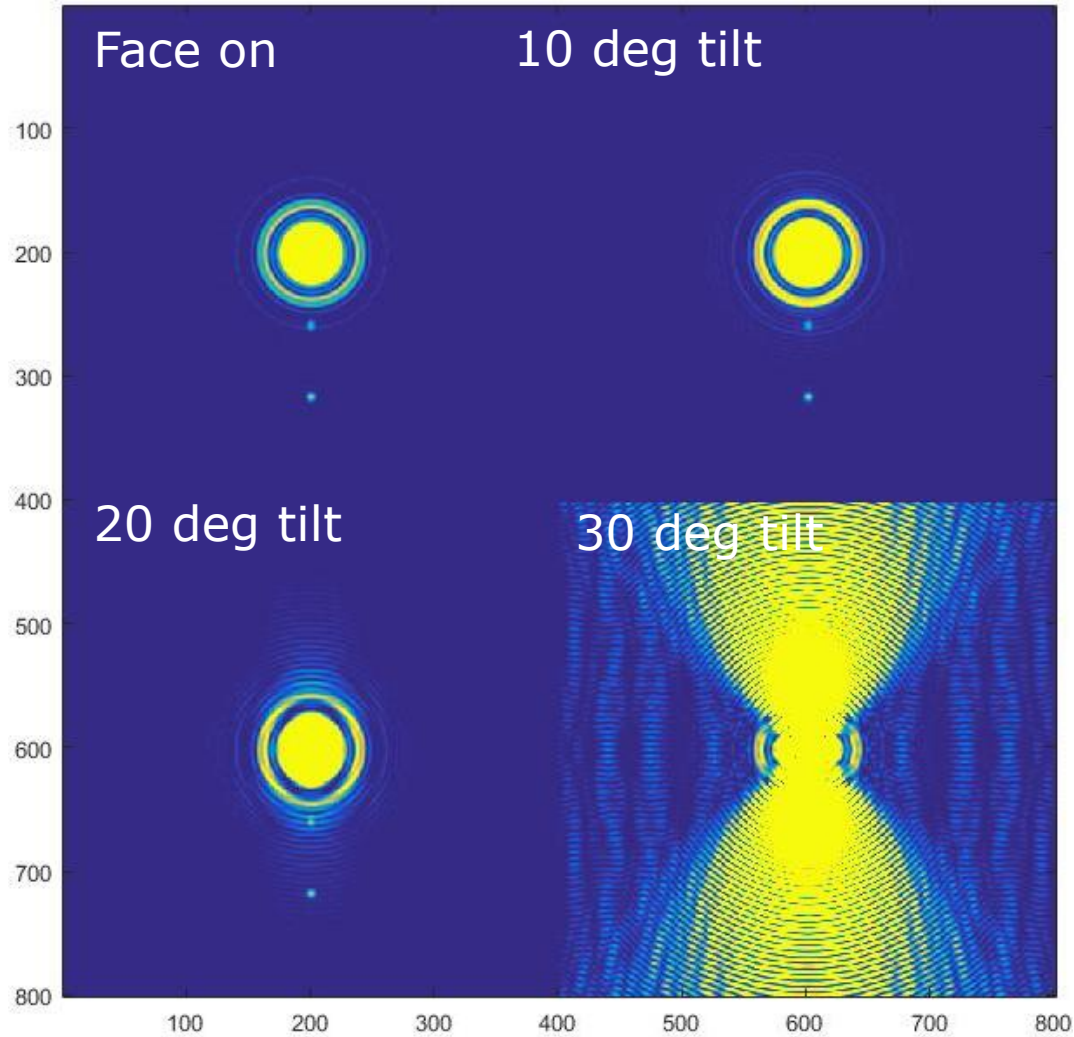
SR=0.2, 1 exozodi



White levels are counts in a 1200 s integration. Optical throughput = 0.5. Bandpass 400-700 nm.

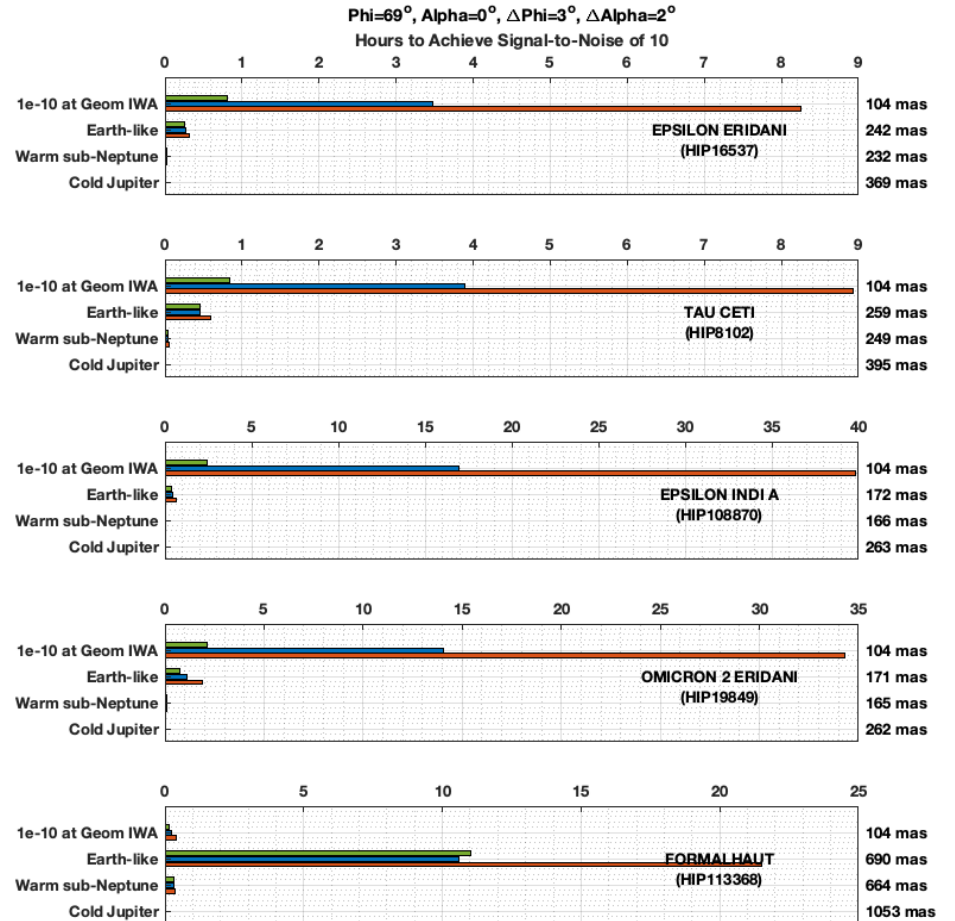
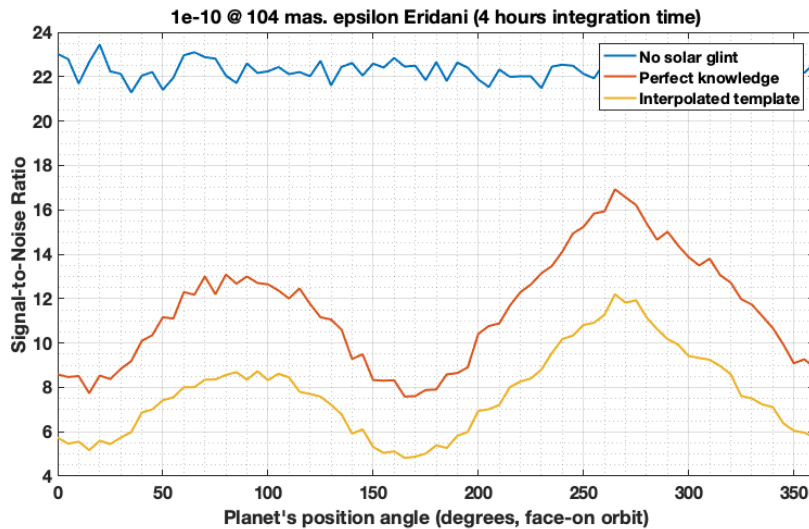
Remote Occulter: Tilting the stashade

Planets are $1e-10$ contrast, at 58 mas and 116 mas.
 Pixel scale 1 mas/pixel. Bandpass 900-1000 nm.



SRM Solar Glint Study

- Look at impact of solar glint lobes on the detection of planets around SRM targets.
 - 615-800 nm band (IWA = 104 mas)
 - QE = 0.69, optical efficiency 0.43
 - EMCCD equivalent (but no cosmic rays)
 - Assume circular orbits



Conclusions

- Matlab-based SISTER is flexible, easy-to-use,
- There are MANY available modes and plotting functions that I have not discussed
 - Orbit visualization
 - Movies and many plotting capabilities
 - Haystacks background objects
<https://asd.gsfc.nasa.gov/projects/haystacks/haystacks.html>
 - Perturbed starshades
- Not yet in SISTER:
 - Telescope-facing surface reflections
 - Micrometeoroid holes
 - Multiple scatter (e.g. between non-coplanar petals)
- SISTER.CALTECH.EDU