Starshade Exoplanet Data Challenge Reference Documentation Broadband Imaging

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The Starshade Exoplanet Data Challenge

The objectives of analyzing the synthetic images are to detect the embedded planets, measure their locations (astrometry) and brightness and planet-star flux ratio (photometry), and determine the S/N of the planet detection. The objective includes extraction of the planet's spectra when spectroscopic data are provided. The objectives also include to measure the brightness, orientation, and (when possible) structures of the exo-zodiacal light. The list of instrumental and astrophysical components are described in each release notes.

The simulations provided by the SEDC were generated with the public software package **SISTER**[1].

Starshade Systems

The SEDC considers the following starshade systems:

1. Starshade Rendezvous Probe: “blue” 425-552 nm, and “green-red” 615-850 nm passbands. SRP, or Rendezvous, in the sequel.
2. Habitable Exoplanet Observatory: “visible” 450-975 nm, and “NIR” 975-1800 nm passbands. HabEx in the sequel.

Initial data will be broad band imaging and future data will include spectroscopic data, following the expected observing sequence during each mission.

The starshade designs are realistic models with a nominal design contrast of 10^{-10} reflecting imperfections in the petal’s shape that are representative of mission requirements. The “contrast” is defined as the ratio between the intensity of starlight averaged in a resolution element at the inner working angle to the peak intensity of the star without the starshade. We expect this ratio at wider angle separation to decrease rapidly and this information is provided in the calibration data (“occulter transmission”).

The starshade simulations provided here include the effects of the residual formation flying motion of the starshade. The starshade will be maintained within ~1m with respect to the line of sight in the lateral plane, and this offset is changing in direction and magnitude every few minutes.

The rest of the instrumental parameters for the optical and detector elements of the systems follow the same specifications as the current best estimates of each mission. Visit IPAC website for details about the Nancy Grace Roman Space Telescope, and for the HabEx observatory, the website cited above.

Exoplanetary Systems

The data challenge considers a system formed by a host star with some specific number and types of exoplanets with a particular inclination one ‘exoplanetary system’. Each exoplanetary system has a set of different scenarios, corresponding to different epochs and exozodiacal cloud models and intensity.

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[1] http://sister.caltech.edu. S.R. Hildebrandt, S.B. Shaklan, E.J. Cady, M.C. Turnbull (2020) “SISTER: Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance”. JATIS. Accepted for publication.

For the SRP mission, the SEDC considers the following 10 exoplanetary systems associated with 4 stars:

1. tau Ceti: 1 and 2.
2. epsilon Indi A: 3 and 4 .
3. sigma Draconis: 5, 6, 7, and 8.
4. beta Canum Venaticorum: 9 and 10.

For the HabEx mission, the SEDC considers the following 8 exoplanetary systems associated with the same 4 stars:

5. tau Ceti: 1 and 2.
6. epsilon Indi: 3 and 4 .
7. sigma Draconis: 5, and 6.
8. beta Canum Venaticorum: 7 and 8.

Each system has a set of scenarios described in the simulated data section. The choice is made to highlight the relevance of the instrumental effects of the starshade system on the scientific results of the analysis. One the most pressing issue that SEDC may help to resolve is how the SNR of planet detections from processing the retrieval of the synthetic images compare with the idealized, input SNR.

As for the exozodiacal dust disk, we provide two physical models with different levels of dust density: i) a smooth exozodiacal dust (meaning that the dust density decreases with semi-major axis smoothly) without resonant structures; and (ii) a resonant cloud model whose structure has some imprint from the gravitational interactions between the dust and the exoplanets. We also include some visual inclination that may vary from one exoplanetary system to another one. The visual inclination ranges from 0 to 90 degrees, except for tau Ceti, where we assume an inclination of 35 degrees consistent with that of the observed outer disk. Exoplanets are assumed to be coplanar with the dust. Both the dust density level and the inclination values are not disclosed and are part of the analysis goals.

Data Format

The simulations and calibration data (PSF and starshade transmission curves) are provided in FITS format. The files contain headers with Keywords containing all relevant disclosed information. Some of the information, such as planet location, flux ratio, albedo, or exozodiacal dust intensity are not provided, as they are part of the blind data analysis goals.

A generic filename has the following syntax:

sister_(R/H)(Scenario #)**_v**(visit #)**_**(exodust model)**ez**(exozodi intensity level #)**_sn**r(SNR level #)**_passband** (in nanometers)**_r**(release #)(degraded_contarst)**.fits**

An example would be:

`sister_R02_v1_sez2_snr1_0425_0552_nm_r2.fits`

The FITS header of each file contains all the relevant information. Here, we summarize it:

The file above would correspond to the second scenario of the Rendezvous mission (R), during its first visit to this system (tau Ceti, scenario #2, recall section Exoplanetary Systems) with an intermediate level of smooth exozodiacal dust (sez) and the lowest level of SNR. The passband is 425-552 nm, aka ‘blue’ and the data file belongs to the complete set of simulated data for Starshade Rendezvous (aka ‘release 2’).

The exodust model can be of two types: smooth, whose label is ‘sez’, or with a resonant structure, whose label is ‘rez’. We also provide three (undisclosed) dust density levels, labeled with 1, 2, and 3. We would like to stress that the indices next to **sez/rez** and **snr** are **not** the intensity of the exozodiacal dust in units of solar system intensity, or the actual SNR of the reference planet, but are simply labels that refer to the three (undisclosed) levels considered: lower, intermediate and higher values. The actual values may also be different between the smooth and resonant cases.

The ending ‘r2’ refers to the ‘second’ (complete) release of Starshade Rendezvous imaging simulations.

If the simulation has a degraded contrast, specifically 10^{-9} versus the nominal case of 10^{-10}, the file ends with ‘_1em9’. Otherwise, that field is empty.

Starshade Rendezvous Imaging Simulations

This is the complete set of broad band imaging simulations, aka release 2. The scenarios in release 1 are included as a subset, although with slightly *different* instrumental parameters. In a future release, we will include spectroscopy of both Starshade Rendezvous and HabEx.

There are a total of **1,440** files that are subdivided into the following subsets:

- 2 starshade contrast scenarios of 1e-10 and of 1e-9 at the IWA with **720** files each.
    - Divided into 2 passbands: 425-552 nm and 615-800 nm with **360** files each.
        - Divided into 10 independent exoplanetary scenarios with **36** files each
            - Divided into 2 physical models of exozodi (‘smooth’ and ‘resonant cloud’) with **18** files each.
                - Divided into 3 levels of dust density with **6** files each.
                    - Divided into 3 SNR levels with **2** files each, and
                        - Divided into 2 visits with **1** file each.

Each SNR level corresponds to a different integration time (recorded in the FITS header of the simulation). The actual value of the SNR for each planet in the simulation is undisclosed and it is one of the analysis goals.

The case of a starshade design with a 10^{-10} contrast at the IWA, which corresponds to an imperfect starshade within mission specifications, is regarded as the *nominal* one for analysis purposes. The one with a contrast of 10^{-9} at the IWA has a larger degradation and also includes the solar glint effect amplified by a factor of 2, as a worst case scenario.

The FOV of the simulated data for both passbands is 65x65 pixels, equivalent to ~1420 mas x 1420 mas (1 pixel in Roman's detector is 21.85 mas x 21.85 mas). The corresponding physical dimension of each simulation (in e.g., AU) depends on the distance to the host star in the simulation. This FOV constitutes in fact a fraction of the entire camera's frame, which is approximately 1024x1024 pixels. The simulated data contain the central area with the more relevant data for the starshade analysis.

The simulated images in the nominal, i.e. 10^{-10} contrast, do not include straylight reflected on the starshade surface from the Earth, the Milky way or other potential straylight sources due to the starshade degradation after micrometeorite collisions. These terms however are estimated to be smaller than the solar glint, which has been included in the synthetic images and do not really represent a missing piece in our simulations. In fact, the simulations with the contrast of 10^{-9} do include the solar glint effect increased by a factor of 2 that accounts for these terms.

We also provide some calibration data, see its corresponding section, that may be helpful to estimate the astrometry and photometry of the simulated data.

The FITS Header of the scenarios provides other information, such as the pixel scale of the images, the passband in consideration, properties of the host star, and other relevant data. An example of the keywords can be seen in the Appendix A section.

Limitations

Some of the limitations of the simulations of this release that will be revisited in the release with spectroscopic data are:

Planets *do not move* during the observation. For most cases, this is a good approximation. In some cases with long integration times, the planet(s) could move over a very few pixels at most. However, this means that the planet(s) are faint and close to the system capability for detection (broad imaging), not mentioning characterization (spectroscopy). Therefore, it is not a good candidate for a future program. We will include planetary motion when we deal with long integration times, e.g., spectroscopy, although we may share the planet's location within some margin based on expected RV ancillary data.

The detector model is an EMCCD in *analogue mode*. The starshade throughput and the type of planets considered in this first release allow one to just use the EMCCD detector in Roman in analogue mode instead of photon counting mode. This simplifies the noise simulations that you may also need to perform. In the future case of spectroscopy, we expect to include a photon counting mode because the photon rate will be significantly lower than in the broad band imaging case.

Calibration data

In order to perform the **broad imaging** data analysis, we provide the following system information:

1. **PSF response**: an averaged PSF response of the starshade-telescope system, obtained using SISTER and it is an accurate representation of the expected optical response. The average is a direct mean value of the PSF response at different wavelengths across the passband under consideration[2]. The PSF response is provided at different angular distances from the starshade center. It is normalized to the PSF response far away from the starshade center, which is equivalent to the telescope's response itself. Optical losses, as the one associated with the secondary and the struts in the case of the Roman telescope (Rendezvous) are included in the simulated data and in the value of the star flux (see later).[3]

   The PSF spatial extent is very large in order to provide 99.5% of the energy contained in the full PSF response. When using the PSF, one may select a portion of the central response and know how much energy is encircled. Similarly, one may use the file to derive the average FWHM far away from the starshade center.

   We provide these PSF files:

   - `psf_averaged_NI2_sedc_1em10_0425_0552_nm`
   - `psf_averaged_NI2_sedc_1em10_0615_0800_nm`
   - `psf_averaged_NI2_sedc_1em9_0425_0552_nm`
   - `psf_averaged_NI2_sedc_1em9_0615_0800_nm`

   The ones with the label '1em10' correspond to the case with a 10^{-10} contrast (at the IWA), whereas the ones with '1em9' correspond to the case with a 10^{-9} contrast (at the

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[2] If the astrophysical signal has a strong dependence on wavelength, the effective PSF would be different. For the case of broad imaging, it may be good enough in order to estimate average values, but we can certainly provide a wavelength dependent PSF if your analysis requires such level of accuracy.

[3] In the case of Rendezvous, if one would like to retrieve the true source counts, there's still a factor 1/0.824664=1.2126 due to the presence of the secondary and the struts supporting it that are obstructing the telescope's aperture. HabEx has an unobstructed telescope design, and there's no additional factor to take into account. We do not expect to use this correction (see the comments on the star flux on the Calibration data section).

IWA). For instance, or Rendezvous and the 425-552 nm passband, `psf_averaged_NI2_sedc_1em10_0425_0552_nm.fits`. The pixel size, angular distances from the starshade center, and other parameters are found in its Header, see also Appendix B for more information and a figure.

2. **Occulter transmission**: an average transmission for the effect due to the starshade diffraction. We compare the flux that would arrive at the telescope with and without the presence of the starshade. The average is a direct mean value of the transmission at different wavelengths across the passband under consideration, which does not vary much across wavelengths (see footnote). This information can be used to retrieve the actual counts from the sources, removing the 'blocking' effect of the starshade. Only, in regions close to or inside the IWA does its value become significantly different to 1.

   We provide the following transmission files:

   - `Starshade_averaged_transmission_NI2_sedc_1em10_0425_0552_nm`
   - `starshade_averaged_transmission_NI2_sedc_1em10_0615_0800_nm`
   - `starshade_averaged_transmission_NI2_sedc_1em9_0425_0552_nm`
   - `starshade_averaged_transmission_NI2_sedc_1em9_0615_0800_nm`

   The ones with the label '1em10' correspond to the case with a 10^{-10} contrast (at the IWA), whereas the ones with '1em9' correspond to the case with a 10^{-9} contrast (at the IWA). For instance, for Rendezvous and the 425-552 nm passband, the filename is `Starshade_averaged_transmission_NI2_sedc_1em10_0425_0552_nm`. See its Header and Appendix C for more information and a figure.

3. **Star flux**: we provide the normalized count rate of the star's flux, integrated over the instrumental passband in consideration, that would be detected in case the starshade were not present (and the detector's parameters set to not saturate the exposures). This is found in the Keyword STARFLX of each simulated data file, see also Appendix A.

   If you divide the estimated counts on the planets, corrected both for the fraction of the energy encircled in your photometric estimation and the starshade transmission, by this value of the star counts, you would derive an estimation of the planet's flux ratio. There is no need to correct for the telescope's blocked area in the case of Rendezvous since this (constant) effect is both included in the star counts and when you estimate the planet counts on the data, so that it cancels out when deriving the ratio. This estimation will be an estimated average of the actual flux ratio that depends on the wavelength dependence of the planet's albedo.

4. **Integration time**: it is found in the FITS header of each simulated file. See Appendix A.

5. **Detector parameters**: they are defined in the FITS header of each simulated file. See Appendix A.

Other calibration data will be included when we release the simulated data with spectroscopy. For instance, the detector's QE, telescope transmission, or the starshade transmission as a function of wavelength. If they were necessary in the study of broad band imaging, we can provide them earlier. Similarly with other system parameters that you may find convenient for your analysis.

FAQ

Q1: Where can I get the simulated data?
A1: You can download them from the SIP website.

Q2: Why does the PSF data have the first/second column swapped?
A2: The FITS files were created with CFITSIO in Matlab. It seems that other programming languages with inverted column/row order may swap the first two indices. The PSF is a square array for each of the angular distances to the starshade center.

Q3: Do the planets move in Keplerian orbits in the simulations?
A3: They do not in the case of broad band imaging. As mentioned in the text above "Planets do not move during the observation. For most cases, this is a good approximation. In some cases with long integration times, the planet(s) could move over a very few pixels at most. However, this means that the planet(s) are faint and close to the system capability for detection (broad imaging), not mentioning characterization (spectroscopy). Therefore, it is not a good candidate for a future program. We will include planetary motion when we deal with long integration times, e.g., spectroscopy, although we may share the planet's location within some margin based on expected RV ancillary data."

Q4: How do we measure the star's flux in each simulation?
A4: The FITS header of each simulation has a keyword called STARFLX. Read point 3 in the section about Calibration data to know how to use it.

Q5: How do I read the FITS files in Matlab?
A5: You can get the FITS header as:

- info=fitsinfo('filename.fits');header=info.PrimaryData.Keywords

You can get the simulated data or the calibration data as:

- data=fitsread('filename.fits', 'Primary');

Q6: How do I generate new noise simulations?
A6: Sometimes you may want to generate new noise realizations once you have a model of the planet or background. These simulations consider a noise model that is the standard case of a CCD run in analogue mode. SISTER noise generator is described in this section "Generating

noise realizations given a simulation" of SISTER's Handbook and can easily be coded up in any other scripting language.

Resources

The SIP website provides some resources, like past presentations. SISTER's manual may also be helpful, although the analysis of the current simulations does not require you to perform any starshade simulation on your own. We provide everything from the starshade that you may need (PSF basis and transmission curves). Other tools, like astrometric or photometric tools can be found elsewhere in any generic astronomical site, or can be programmed by yourself, including noise simulations that may be necessary to estimate the error bars of your results.

Acknowledgments

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If you publish results based partly on the simulations provided here, please acknowledge it in the following form:

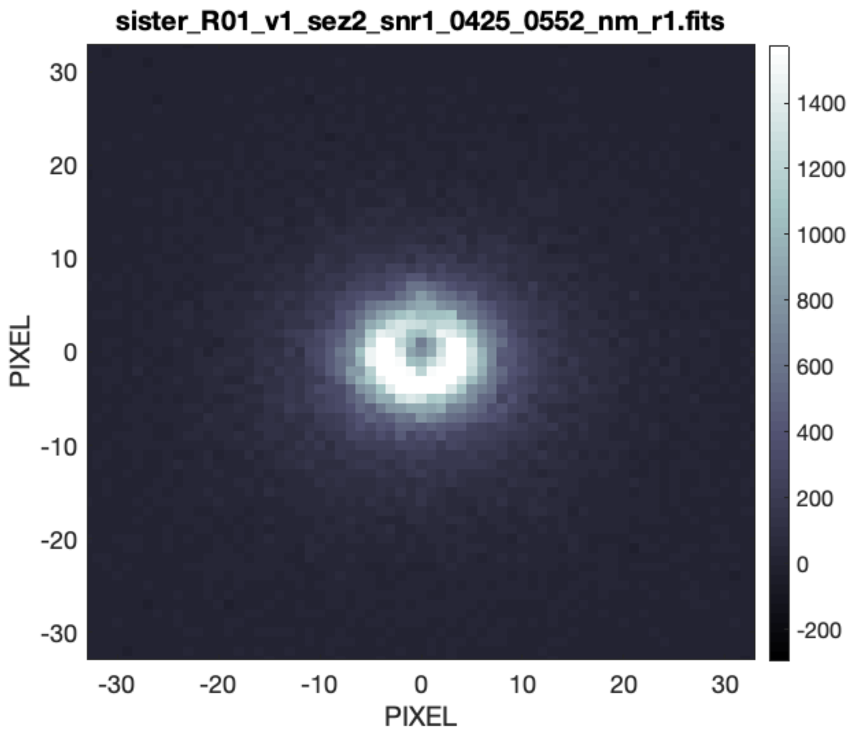
1. An acknowledgment statement – "Some of the results in this paper have been derived using starshade simulations from the SISTER package."
2. At the first use of the SISTER acronym, a footnote placed in the main body of the paper referring to the SISTER website – currently http://sister.caltech.edu and authors S.R. Hildebrandt, and S.B. Shaklan.
3. A reference to S.R. Hildebrandt, S.B. Shaklan, E.J. Cady, M.C. Turnbull (2021) "Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance". https://doi.org/10.1117/1.JATIS.7.2.021217

Acronyms

EMCCD: Electron multiplier CCD
FOV: Field of View
HabEx: Habitable Exoplanet Observatory
IWA: Inner Working angle. The angular size of the starshade as eem from the telescope
SEDC: Starshade Exoplanet Data Challenge
SISTER: Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance
SNR: signal-to-noise ratio
SRP: Starshade Rendezvous Probe

Appendix A: FITS Header for the data simulations

This is an image for the file `sister_R01_v1_sez2_snr1_0425_0552_nm_r1.fits`.



This is the FITS header for the same file `sister_R01_v1_sez2_snr1_0425_0552_nm_r1.fits`. Notice that the total integration time is 1686 seconds (`INTTIME`).

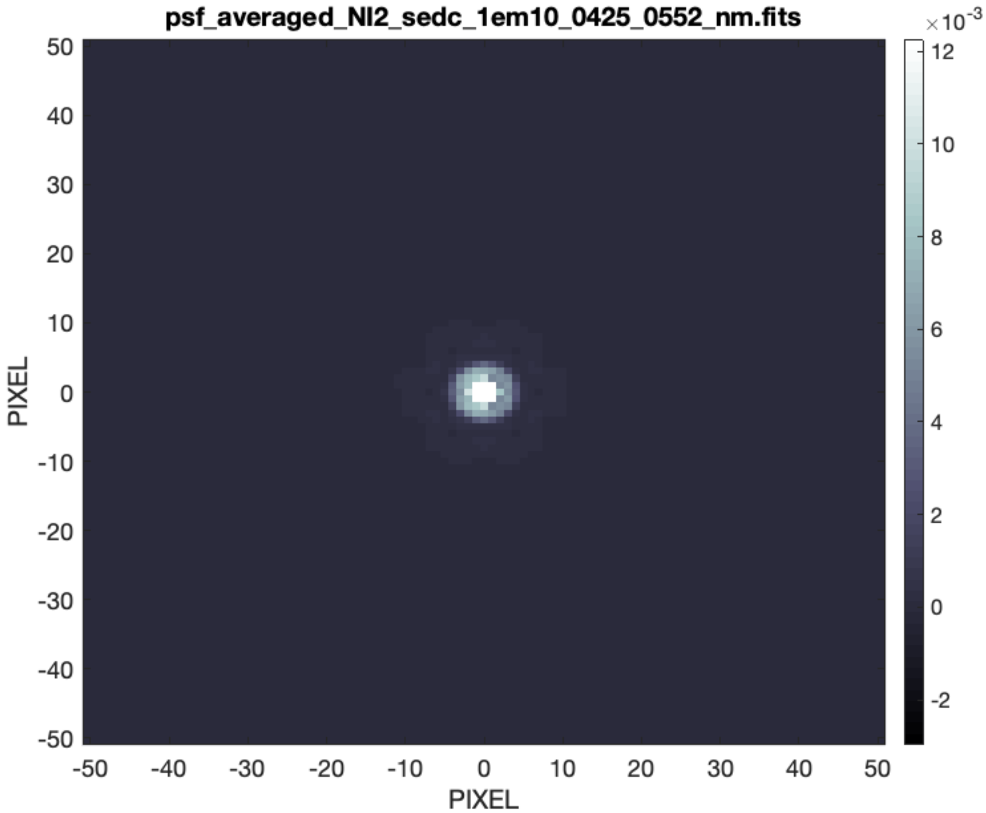
```
{'SIMPLE'  }    {'T'                 }    {' file does conform to FITS stand...'}
{'BITPIX'  }    {[              -64]}    {' number of bits per data pixel  ...'}
{'NAXIS'   }    {[                2]}    {' number of data axes            ...'}
{'NAXIS1'  }    {[               67]}    {' length of data axis 1          ...'}
{'NAXIS2'  }    {[               67]}    {' length of data axis 2          ...'}
{'EXTEND'  }    {'T'                 }    {' FITS dataset may contain extens...'}
{'COMMENT' }    {0x0 char            }    {'  FITS (Flexible Image Transport...'}
{'COMMENT' }    {0x0 char            }    {'  and Astrophysics', volume 376,...'}
{'SIM'     }    {'R01'               }    {' starshade system and scenario  ...'}
{'VISIT'   }    {[                1]}    {' visit number, aka epoch        ...'}
{'XCENTER' }    {[               33]}    {' pixel x-coordinates in 00LL con...'}
{'UNITS'   }    {'normalized counts' }    {' total number of e- divided by t...'}
{'FF'      }    {[                1]}    {' formation flying. 0: not includ...'}
{'MINLAM'  }    {[              425]}    {' minimum simulated wavelength (n...'}
{'MAXLAM'  }    {[              552]}    {' maximum simulated wavelength (n...'}
{'DELTALAM'}    {[                5]}    {' PSF basis. Wavelength spacing (...'}
{'PIXSCALE'}    {[          21.8500]}    {' (mas=milli-arcsec)             ...'}
{'DIAMTEL' }    {[           2.3600]}    {' (meters)                       ...'}
{'YCENTER' }    {[               33]}    {' pixel y-coordinates in 00LL con...'}
{'OBSCURED'}    {[           0.4187]}    {' effective ratio of secondary&st...'}
```

```
{'JITTER'  }    {[                14]}    {' pointing jitter RMS (mas)       ...'}
{'DESIGN'  }    {'NI2_test_case_1em10'}    {' SS design (NI2: Rendezvous, TV3...'}
{'SGLINT'  }    {'nominal'           }    {' solar glint model             ...'}
{'TELDIST' }    {[             37242]}    {' SS-Telescope range (kilometers)...'}
{'GEOIWA'  }    {[                72]}    {' Geometric IWA (mas=milli-arcsec...'}
{'STARNAME'}    {'tau Ceti'          }    {' star's common name            ...'}
{'VSTAR'   }    {[            3.5000]}    {' star's V magnitude            ...'}
{'STARDIST'}    {[            3.6500]}    {' star's distance (parsec, 1 AU=1...'}
{'STARMASS'}    {[            0.7830]}    {' star's mass divided by solar ma...'}
{'STARRAD' }    {[            0.7930]}    {' star's radius divided by solar ...'}
{'STARLUM' }    {[            0.7830]}    {' star's luminosity divided by so...'}
{'STARTEMP'}    {[              5780]}    {' star's temperature (K)        ...'}
{'STARFLX' }    {[         191231902]}    {' star's total detected flux (nor...'}
{'EXOZODI' }    {'SMOOTH CLOUD'      }    {' exozodi spatial distribution   ...'}
{'EXOLVL'  }    {[                 2]}    {' exozodi intensity *label*      ...'}
{'SNRLVL'  }    {[                 1]}    {' SNR level *label*             ...'}
{'INTTIME' }    {[              1686]}    {' total integration time (sec)   ...'}
{'FRMTIME' }    {[                60]}    {' integration time of each indivi...'}
{'NFRAMES' }    {[                31]}    {' actual number of individual fra...'}
{'DETTYPE' }    {'emccd am'          }    {' detector type: CCD, EMCCD AM or...'}
{'DETGAIN' }    {[               200]}    {' detector's gain (dimensionless)...'}
{'ENF2'    }    {[                 2]}    {' excess noise factor squared (di...'}
{'READOUT' }    {[               100]}    {' read-out noise (e/pix/frame)   ...'}
{'CIC'     }    {[            0.0200]}    {' clock induced charges (e/pix/fr...'}
{'DARKCURR'}    {[        4.2222e-04]}    {' dark current (e/pix/sec)       ...'}
{'POISSONL'}    {[                10]}    {' Poisson -> Normal (with continu...'}
{'END'     }    {0x0 char            }    {0x0 char                          }
```

The files

Appendix B: FITS Header for the PSF response

Here is an image of the PSF at the geometric IWA of the Rendezvous, 425-552 nm passband, `psf_averaged_NI2_sedc_1em10_0425_0552_nm.fits`. One can see that the keyword DESIGN shows NI2_sedc_1em10, which is the starshade design with the 10^{-10} contrast (at the IWA). One may notice a slight left/right asymmetry due to the starshade diffraction. Close to the starshade center, the PSF response gets more affected by the starshade diffraction. The PSF spatial extent is very large in order to provide 99.5% of the energy contained in the full PSF response. When using the PSF, one may select a portion of the central response and know how much energy is encircled. Similarly, one may use the file to derive the average FWHM far away from the starshade center.



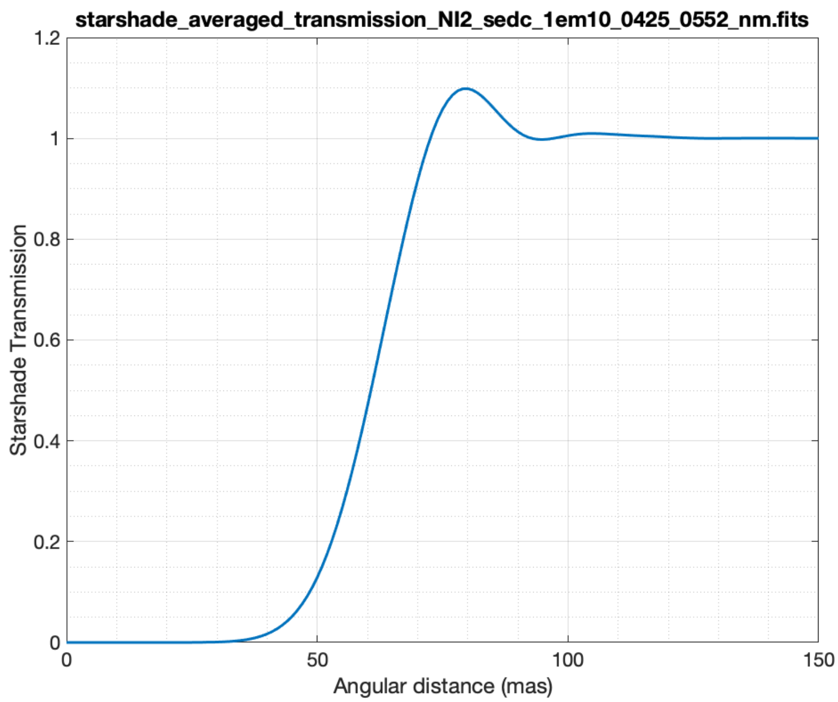
Beware that the first and second indices of the PSF array may be swapped (See FAQ). In the example below: , the PSF array in the case of the 425-552 nm passband the shape of the array should be 151x103x103, whereas it should be 221x149x149 in the case of the 615-800 nm passband. The first dimension corresponds to the angular distance to the starshade's center measured in mas. That is, the first index corresponds to 0 mas distance, i.e, on-axis, whereas the last index corresponds to 150 mas distance. The 615-800 nm file extends to farther angular distances than in the 425-552 nm case. This is due to the fact that the optical effects of the starshade are noticed at larger angular distances in the case of the 615-800 nm passband than in the case of the 425-552 nm passband. Remember that the angular size of each pixel can be read from the file's HEADER. In the case of Starshade Rendezvous it is 21.85 mas.

```
{'SIMPLE'  }    {'T'            }    {' file does conform to FITS standard            '   }
    {'BITPIX'  }    {[          -64]}    {' number of bits per data pixel                  '   }
    {'NAXIS'   }    {[            3]}    {' number of data axes                            '   }
    {'NAXIS1'  }    {[          103]}    {' length of data axis 1                          '   }
    {'NAXIS2'  }    {[          151]}    {' length of data axis 2                          '   }
    {'NAXIS3'  }    {[          103]}    {' length of data axis 3                          '   }
    {'EXTEND'  }    {'T'            }    {' FITS dataset may contain extensions            '   }
    {'COMMENT' }    {0x0 char       }    {'  FITS (Flexible Image Transport System) format ...'}
    {'COMMENT' }    {0x0 char       }    {'  and Astrophysics', volume 376, page 359; bibco...'}
    {'UNITS'   }    {'Dimensionless' }    {' normalized <PSF> @ different angles from the SS'   }
    {'PSFSIZE' }    {'103x103'      }    {' pixels                                         '   }
```

```
{'NDIST'   }    {[          151]}    {' number of radial positions                    '   }
{'MINDIST' }    {[            0]}    {' minimum angular distance (mas=milli-arcsec)    '   }
{'MAXDIST' }    {[          150]}    {' maximum angular distance (mas=milli-arcsec)    '   }
{'DDIST'   }    {[            1]}    {' step between consecutive PSF (mas=milli-arcsec)'   }
{'MINLAM'  }    {[          425]}    {' minimum PSF wavelength (nanometers)            '   }
{'MAXLAM'  }    {[          552]}    {' maximum PSF wavelength (nanometers)            '   }
{'DELTALAM'}    {[            5]}    {' PSF basis. Wavelength spacing (nanometers)     '   }
{'PIXSCALE'}    {[      21.8500]}    {' (mas=milli-arcsec)                             '   }
{'DIAMTEL' }    {[       2.3600]}    {' (meters)                                       '   }
{'XCENTER' }    {[           51]}    {' pixel x-coordinates in 00LL convention         '   }
{'YCENTER' }    {[           51]}    {' pixel y-coordinates in 00LL convention         '   }
{'OBSCURED'}    {[       0.4187]}    {' effective ratio of secondary&struts to DIAMTEL '   }
{'JITTER'  }    {[           14]}    {' pointing jitter RMS (mas)                      '   }
{'DESIGN'  }    {'NI2_sedc_1em10'}   {' SS design (NI2: Rendezvous, TV3: HabEx)        '   }
{'TELDIST' }    {[        37242]}    {' SS-Telescope range (kilometers)                '   }
{'GEOIWA'  }    {[           72]}    {' Geometric IWA (mas=milli-arcsec)               '   }
{'END'     }    {0x0 char       }    {0x0 char                                             }
```

Appendix C: FITS Header for the starshade transmission

The FITS files with the occulter (aka starshade) transmission are two dimensional. For instance for Rendezvous and the 425-552 nm passband, `starshade_averaged_transmission_NI2_sedc_1em10_0425_0552_nm` has this shape (2x151). The first dimension corresponds to the angular distance to the starshade's center measured in mas. That is, the first index corresponds to 0 mas distance, i..e, on-axis, whereas the last index corresponds to 150 mas distance. In the case of the 615-800 nm passband, the shape is (2x221). The 615-800 nm file extends to farther angular distances than in the 425-552 nm case. This is similar as with the PSF file, and it is due to the fact that the optical effects of the starshade are noticed at larger angular distances in the case of the 615-800 nm passband than in the case of the 425-552 nm passband. The second index corresponds to the transmission. This is a figure from the file
`starshade_averaged_transmission_NI2_sedc_1em10_0425_0552_nm`



The ‘bump’ near the IWA region is a known effect due to Fresnel diffraction. The FITS header of the file `starshade_averaged_transmission_NI2_sedc_1em10_0425_0552_nm.fits` reads:

```
{'SIMPLE'  }    {'T'                           }    {' file does conform to FITS standard            '  }
{'BITPIX'  }    {[                          -64]}    {' number of bits per data pixel                 '  }
{'NAXIS'   }    {[                            2]}    {' number of data axes                           '  }
{'NAXIS1'  }    {[                          151]}    {' length of data axis 1                         '  }
{'NAXIS2'  }    {[                            2]}    {' length of data axis 2                         '  }
{'EXTEND'  }    {'T'                           }    {' FITS dataset may contain extensions           '  }
{'COMMENT' }    {0x0 char                      }    {'  FITS (Flexible Image Transport System) format ...'}
{'COMMENT' }    {0x0 char                      }    {'  and Astrophysics', volume 376, page 359; bibco...'}
{'UNITS1'  }    {'angular distance from SS center'}    {' (mas=milli-arcsec)                            '  }
{'UNITS2'  }    {'dimensionless'               }    {' normalized SS transmission @ different angles '  }
{'NDIST'   }    {[                          151]}    {' number of radial positions                    '  }
{'MINDIST' }    {[                            0]}    {' minimum distance (mas=milli-arcsec)           '  }
{'MAXDIST' }    {[                          150]}    {' maximum distance (mas=milli-arcsec)           '  }
{'DDIST'   }    {[                            1]}    {' step between consecutive PSF (mas=milli-arcsec)'  }
{'MINLAM'  }    {[                          425]}    {' minimum PSF wavelength (nanometers)           '  }
{'MAXLAM'  }    {[                          552]}    {' maximum PSF wavelength (nanometers)           '  }
{'DELTALAM'}    {[                            5]}    {' PSF basis. Wavelength spacing (nanometers)    '  }
{'PIXSCALE'}    {[                      21.8500]}    {' (mas=milli-arcsec)                            '  }
{'DIAMTEL' }    {[                       2.3600]}    {' (meters)                                      '  }
{'OBSCURED'}    {[                       0.4187]}    {' effective ratio of secondary&struts to DIAMTEL '  }
{'JITTER'  }    {[                           14]}    {' pointing jitter RMS (mas)                     '  }
{'DESIGN'  }    {'NI2_sedc_1em10'              }    {' SS design (NI2: Rendezvous, TV3: HabEx)        '  }
{'TELDIST' }    {[                        37242]}    {' SS-Telescope range (kilometers)               '  }
{'GEOIWA'  }    {[                           72]}    {' Geometric IWA (mas=milli-arcsec)              '  }
{'END'     }    {0x0 char                      }    {0x0 char                                        }
```

Appendix D: Release 1

The first release of starshade simulations (01/27/21) had a limited set of astrophysical and instrumental scenarios compared with the complete set described above. Moreover, after release 1, we refined some key aspects of the instrumental model. Release 1 should be considered as a first release, whereas the *complete* set of Starshade Rendezvous Imaging Simulations is the set to derive results for publication and more impactful results.

We keep for the record the documentation that went with release 1.

The first release consisted of one observation of the **10** different exoplanetary scenarios for **Rendezvous** and its blue passband (**425-552 nm**).

The simulations correspond to **1** epoch (visit). The location of the planet(s) is undisclosed.

The simulations consider a **smooth** model of exozodiacal light with an (undisclosed) intermediate intensity.

We provide **3** levels of SNR. That is, three different integration times. Thus, the total number of files is **30** (recall that the total number of particular scenarios for each exoplanetary system is 36, so release 1 is only a fraction of the whole simulated data that will be released in broad imaging).

The FOV of the simulated data is 67x67 pixels. The angular size per pixel is 21.85 mas, so that the FOV is approximately 1.464 arcsec x 1.464 arcsec. The corresponding physical dimension (in e.g., AU) depends on the star observed. This FOV constitutes a fraction of the entire camera's frame, which is approximately 22.4 arcsec x 22.4 arcsec. The 67x67 central area contains the more relevant data for the starshade analysis.

We also provide some calibration data, see its corresponding section, that may be helpful to estimate the astrometry and photometry of the simulated data.

The FITS Header of the scenarios provides other information, such as the pixel scale of the images, the passband in consideration, properties of the host star, and other relevant data. A sample of the Keywords can be seen in the Appendix A section.

Some of the limitations of the simulations of this release that will be revisited in forthcoming releases are:

Planets do not move during the observation. For most cases, this is a good approximation. In some cases with long integration times, the planet(s) could move over a very few pixels at most. However, this means that the planet(s) are faint and close to the system capability for detection (broad imaging), not mentioning characterization (spectroscopy). Therefore, it is not a good candidate for a future program. We will include planetary motion when we deal with long integration times, e.g., spectroscopy, although we may share the planet's location within some margin based on expected RV ancillary data.

The detector model is an EMCCD in analogue mode. The starshade throughput and the type of planets considered in this first release allow one to just use the EMCCD detector in Roman in analogue mode instead of photon counting mode. In the future case of spectroscopy, we expect to include a photon counting mode because the photon rate will be significantly lower than in the broad band imaging case.

The synthetic images in release #1 do not include straylight reflected on the starshade surface from the Earth, the Milky way or other potential straylight sources due to the starshade degradation after micrometeorite collisions. These terms however are estimated to be smaller than the solar glint, which has been included in the synthetic images.