

Standardized Coronagraph Parameters for Input into Yield Calculations

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Christopher Stark
John Krist

To estimate the science yields of future telescopes, yield modeling codes must adopt parameters describing the performance of the telescope-instrument combination. Adopting standard parameters and file formats would help streamline this process, both for those modeling the yield and those modeling the instruments. As such, this document details a set of instrument model files that would form a useful set of standard inputs for yield codes.

Important definitions and notes

- *D*: the circumscribed diameter of the primary mirror. Wherever units of λ/D are referenced, *D* is the circumscribed diameter of the primary, **not** the inscribed diameter or the projected Lyot stop diameter.
- *Primary illuminated area*: in this document, we consider the “primary” the effective entrance pupil of the telescope. It includes the primary mirror geometry itself and all geometric obstructions due to the secondary and support structures projected onto the primary. Thus the primary illuminated area of an on-axis telescope is smaller than the primary illuminated area of an off-axis telescope.
- *Throughput*: we will differentiate between two types of throughput. The first is the coronagraph’s mathematical throughput, which is quantified via the input files described below. All other factors of throughput, including all mirror reflectivities, detector QE, transmissive optics, polarizers, etc. are included in a separate throughput factor *T* (note that *T* does not include the geometric obscuration of the secondary and/or support structures, as those terms are included in the primary illuminated area).
- All broadband calculations of the image maps below should be performed assuming a flat object spectrum.
- All files are to be in fits format. All maps must be at least Nyquist sampled. All files are to be accompanied by a header as described below.

- When supplying values that are in units of **pixel coordinates**, use 00LL convention. 00LL is an acronym I just made up, which means that the lower-left (LL) pixel in the image has **pixel indices** of (0,0), and the **pixel coordinates** of the center of the LL pixel are at (0.5,0.5). The LL corner of the LL pixel has coordinates (0,0) and the upper-right corner of the LL pixel has coordinates (0.999...,0.999...). E.g., the xcenter and ycenter parameters that will be included in your files indicate the **pixel coordinates** of the center of an image. If your image is centered on a given pixel, the pixel coordinates will have half-integer values. If your image is centered on the gap between pixels, your pixel coordinates will have integer values.

Headers

All fits files should include the units of the data product in the header and the following minimum list of parameters with values and units indicated:

- PIXSCALE: the pixel scale in units of λ/D , where λ is the effective central wavelength of the bandpass
- LAMBDA: the value of the central wavelength of the bandpass in microns
- MINLAM: the shortest wavelength of the passband in microns
- MAXLAM: the longest wavelength of the passband in microns
- D: the circumscribed diameter D of the primary mirror in m
- XCENTER: the center of the image in “00LL” pixel coordinates (see list of notes at beginning of document)
- YCENTER: the center of the image in “00LL” pixel coordinates (see list of notes at beginning of document)
- OBSCURED: the fraction of the aperture area that is obscured by the secondary, struts, gaps, or other deviation from a circular unobscured aperture of circumscribed diameter D

In addition, the stellar intensity map must include the following additional parameter:

- JITTER: RMS jitter per axis in mas (=0 if effect is ignored)
- UNITS: a string specifying the units of the data

File 1: Stellar intensity map**File Name = ‘stellar_intens.fits’**

A unitless 3D array of stellar intensity I as a function of $(x, y, \theta_{\text{star}})$, where the first 2 indices are pixel coordinates and the third index is stellar angular diameter. The values in this stellar intensity map are equal to the stellar count rate in a given pixel divided by the total stellar count rate entering the coronagraph. The stellar intensity map should not include reductions due to typical optical throughput factors like mirror reflectivities, transmissivities, and detector QE, but should include reductions due to apodizers, Lyot stops, diffraction effects, etc. (without a coronagraph, the total of I should be unity).

File 2: Stellar diameter list**File Name = ‘stellar_intens_diam_list.fits’**

A vector of stellar diameter values (in units of λ/D), corresponding to the values assumed for the 3rd dimension of the normalized stellar intensity map. The stellar diameters considered must adequately sample stars ranging in size from 0 – 10 mas for a ~16 m telescope. The vast majority of main sequence target stars will have angular diameters < 1 mas; a handful have angular diameters greater than a few mas, including the nearby Alpha Centauri system. We suggest values of λ/D from 0 – 3, with higher resolution at the small end. Here is an example list that works well.

```
0.0000000  0.005000000  0.010000000  0.020000000  0.030000000  0.040000000
0.050000000  0.060000000  0.070000000  0.080000000  0.090000000  0.100000000
0.150000000  0.200000000  0.250000000  0.300000000  0.350000000  0.400000000
0.450000000  0.500000000  0.600000000  0.700000000  0.800000000  0.900000000
1.0000000  1.5000000  2.0000000  2.5000000  3.0000000
```

Files 1 and 2 are intended to be used as follows to obtain a photon count rate at (x, y) for a given star:

1. For a given star with a specific value of θ_{star} , perform a linear interpolation over the third dimension of the intensity array to approximate the 2D stellar intensity map for that star.
2. Multiply the values of this 2D intensity map $I(x, y)$ by the stellar count rate received by the primary, $F_0 10^{-0.4m_V} A \Delta\lambda$, where F_0 is in units of photons per unit area per unit wavelength per unit time, A is the primary illuminated area (see definition above), and $\Delta\lambda$ is the wavelength bandpass.
3. Multiply by T , which includes all remaining optical throughput factors ignored by the coronagraph’s mathematical throughput (see definition above).
4. Multiply by the number of map pixels in the photometric aperture, i.e. Ω/θ^2 , where Ω is the solid angle of the photometric aperture in steradians and θ is the map’s pixel scale in radians.

$$\text{CR}_{b, \star} = F_0 10^{-0.4m_V} I \frac{\Omega}{\theta^2} A T \Delta\lambda,$$

File 3: Off-Axis PSF maps

File Name = 'offax_psf.fits'

A 3D array of field PSF maps as a function of $(x,y,offset)$. The first 2 indices are standard pixel indices of a 2D image. The third index corresponds to a shift of the PSF by a given astrophysical offset, and is of length N_{offsets} . These are identical to the stellar intensity map, but have non-zero astrophysical offsets. Just like the stellar intensity maps, the off-axis PSF maps are normalized to the total count rate entering the coronagraph. Only coronagraph mathematical throughput is accounted for—additional throughput factors like mirror reflectivity and QE are left out.

File 4: PSF offset list

File Name = 'offax_psf_offset_list.fits'

A $2 \times N_{\text{offsets}}$ array containing the (x,y) values of each astrophysical offset in units of λD . If all x are identical or all y are identical, such that all offsets are along a single axis, the offsets will be assumed to be a function of radial displacement only. Note that the offsets should adequately sample the field dependent variations of the PSF, especially near the edge of the occulter, such that rapid changes in the PSF are not missed and interpolation is approximately valid.

Files 3 and 4 are intended to be used as follows to calculate the planet's count rate *within a given photometric aperture* of radius ρ . To do so, we must first compute a map of the planet's photometric throughput $\Upsilon(x,y)$:

1. For each astrophysical offset, perform centroid to measure the center of the off-axis PSF, then measure the flux exiting the coronagraph Υ contained within a photometric aperture of radius ρ .
2. Interpolate to form a 2D map of $\Upsilon(x,y)$. Note that if the provided astrophysical offsets are along 1 dimension only (all x offsets are identical, or all y offsets are identical), the PSF will be assumed to be a function of radial offset only.
3. For a planet at a given astrophysical offset (x,y) , multiply the value of $\Upsilon(x,y)$ by the planet photon count rate received by the primary illuminated area, $F_0 10^{-0.4(m_V + \Delta\text{mag})} A \Delta\lambda$.
4. Finally, multiply by all additional throughput factors, T .

$$\text{CR}_p = F_0 10^{-0.4(m_V + \Delta\text{mag}_{\text{obs}})} A \Upsilon T \Delta\lambda,$$

File 5: Sky Transmission Map

File Name = 'sky_trans.fits'

A unitless 2D array, $T_{sky}(x,y)$, of the mathematical coronagraphic throughput of infinitely extended sources; it is the projection of the occulter transmission pattern onto the sky, including reduction by the Lyot stop. This includes the mathematical coronagraphic throughput only and additional throughput factors like reflectivity and QE should be left out.

File 5 is intended to be used as follows to obtain the count rate of the local zodi at position (x,y) via the following steps:

1. Multiply the sky transmission map $T_{sky}(x,y)$ by the count rate received by the primary illuminated area per unit solid angle, $F_0 10^{-0.4z} A \Delta\lambda$, where z is the surface brightness of the zodi in units of magnitudes per unit solid angle (e.g., the median V band brightness of the local zodi at a solar longitude of 135 degrees is $z = 23$ mag arcsec⁻²).
2. Multiply by the solid angle of the photometric aperture, Ω .
3. Multiply by any additional throughput factors, T .

$$CR_{b,zodi} = F_0 10^{-0.4z} \Omega A T_{sky} T \Delta\lambda,$$

For exozodi, simply replace z with the appropriate value.