Standardized Coronagraph Parameters for Input into Yield Calculations

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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

- *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. 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 2 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 (see above).

- 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 at the end of this document.

File 1: Stellar intensity map

A unitless 3D array of stellar intensity I as a function of $(x,y,\theta_{\mathrm{star}})$, 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 incident on the primary illuminated area (see definition above). The stellar intensity map should not include reductions due to throughput factors like mirror reflectivities, QE, polarizers, etc. (without a coronagraph, the total of I should be unity).

One can use this intensity map to obtain a photon count rate at (x,y) for a given star via the following steps:

1. For a given star with a specific value of θ_{star}, perform a linear interpolation over the third dimension of the normalized intensity array to approximate the 2D stellar intensity map for that star.
2. Multiply the values of this 2D normalized intensity map I at (x,y) by the stellar count rate received by the primary, $F_0 10^{-0.4 m_V} A\Delta\lambda$, where F_0 is in units of photons per unit area per unit wavelength per unit time, A is the primary illuminated area, and $\Delta\lambda$ is the wavelength bandpass.
3. Multiply by T, which includes all throughput factors except for 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.

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

File 2: Stellar diameter list

A vector of stellar diameter values (in mas), corresponding to the values assumed for the 3rd dimension of the normalized stellar intensity map. The stellar diameters considered must be adequately sampled such that interpolation over angular diameters from 0 – 10 mas is valid. 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.

File 3: Off-Axis PSF maps

A 3D array of field PSF maps as a function of (*x,y,offset*). The first 2 indices are standard pixel coordinates of a 2D image. The third index corresponds to a shift of the PSF by a given offset, and is of length N_{offsets}. All offsets must center the field PSF on a pixel. The PSF maps are normalized to the total count rate received by the primary illuminated area (see definition above). Only coronagraph mathematical throughput is accounted for—additional throughput factors like mirror reflectivity and QE are left out.

With this map, one can calculate the planet 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. Interpolate each offset PSF to measure the fraction of the PSF contained within the photometric aperture radius ρ as a function of offset. Note that if the provided offsets are along 1 dimension only (only x offsets are provided, or only y offsets are provided), the PSF will be assumed to be a function of radial offset only.
2. Generate a 2D map of (x,y) offsets
3. Interpolate to get $\Upsilon(x,y)$, a 2D map of PSF fractions contained within ρ, i.e. the coronagraphic throughput for a point source at (x,y) given photometric aperture radius ρ. Once we have $\Upsilon(x,y)$ we can continue as follows to compute the planet's count rate:

4. For a planet at a given (x,y), multiply the value of $\Upsilon(x,y)$ by the planet photon count rate received by the primary illuminated area, $F_0 10^{-0.4(m_V+\Delta mag)} A\Delta\lambda$.
5. Finally, multiply by all additional throughput factors, T.

$$\mathrm{CR_p} = F_0\, 10^{-0.4(\mathrm{m}_V + \Delta\mathrm{mag_{obs}})}\, A\, \Upsilon\, T\, \Delta\lambda,$$

File 4: PSF offset list
A $2\mathrm{x}N_{\mathrm{offsets}}$ array containing the (x,y) values of each offset in units of λ/D. All offsets should place the field PSF in the center of a pixel. If all x=0 or all y=0, 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.

File 5: Sky Transmission Map
A unitless 2D array, $T_{\mathrm{sky}}(x,y)$, 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 (for a shearing VNC it would include the transmission fringes). This includes the mathematical coronagraphic throughput only and additional throughput factors like reflectivity and QE should be left out.

With this map, one can obtain the count rate of the local zodi at position (x,y) via the following steps:

1. Multiply the sky transmission map $T_{\mathrm{sky}}(x,y)$ 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.

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

For exozodi, simply replace z with the appropriate value.

Headers
All fits files should include the following minimum list of parameters and their values in the header:

- 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
- MINLAMBDA: the shortest wavelength of the passband in microns
- MAXLAMBDA: the longest wavelength of the passband in microns

- D: the value of *D* in m
- XCENTER: the coordinate of the image center in pix
- YCENTER: the coordinate of the image center in pix

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

- JITTER: RMS jitter per axis in mas (=0 if effect is ignored)

The above parameters should be added to the header with units listed in the parameter comments. An example IDL call of such is:
IDL> sxaddpar, header, 'PIXSCALE', 0.3, 'pixel scale in units of lambda/D'