pyEDITH: A coronagraphic exposure time calculator for the Habitable Worlds Observatory

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Software

- Review
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Summary

pyEDITH is a Python-based coronagraphic exposure time calculator built for the recommended NASA flagship mission, the Habitable Worlds Observatory (HWO), tasked with searching for signs of habitability and life in dozens of nearby exoplanet systems. pyEDITH is designed to simulate wavelength-dependent exposure times and signal-to-noise ratios (S/N) for direct imaging observations. pyEDITH considers realistic engineering specifications and user-defined target information to calculate synthetic HWO observations of Earth-like exoplanets. We present a schematic of the pyEDITH framework in Figure 1.

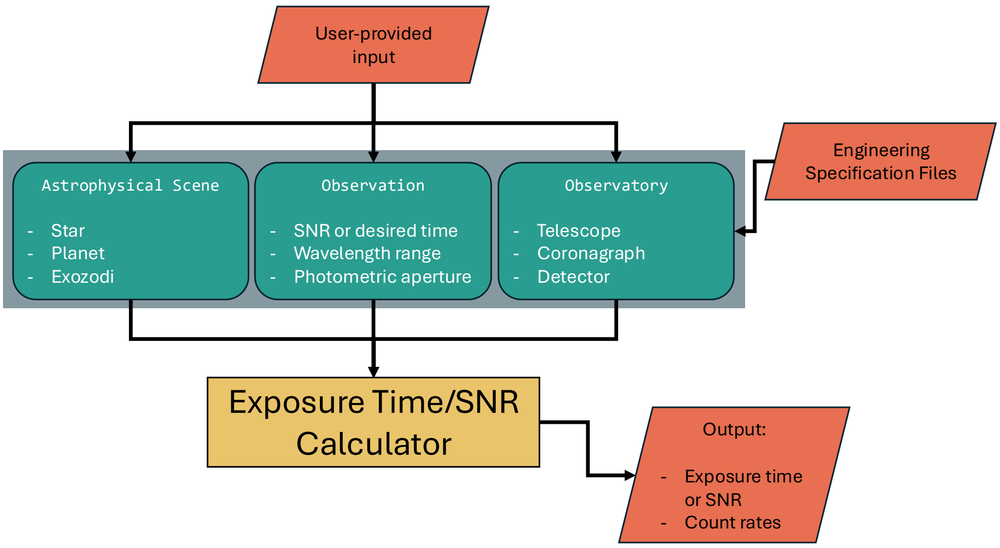

Figure 1: A schematic of the pyEDITH components and their relationships, and the data flow from inputs to final calculations.

Statement of need

pyEDITH is used to develop the exoplanet detection and characterization capabilities of the Habitable Worlds Observatory mission. By implementing the Altruistic Yield Optimizer (Stark et al., 2014) framework in Python, with updated mathematical formalism[1] (Stark et al., 2019), pyEDITH enables easier integration with modern astronomical workflows. pyEDITH was designed

[1] https://starkspace.com/code/hwo_etc.zip

to be used by the scientific community at all skill levels for understanding the capabilities and limitations of different HWO architectures for exoplanet analyses. The `pyEDITH` package includes API documentation[2], tutorial notebooks, and has been used by forthcoming scientific publications (Alei et al., 2025; Currie et al., 2025).

Mathematical formalism

Mathematically, exposure times are calculated as:

$$\tau = (\mathrm{S/N})^2 \left(\frac{\mathrm{CR_p} + \alpha\ \mathrm{CR_b}}{\mathrm{CR_p^2} - (\mathrm{S/N})^2\ \mathrm{CR_{nf}^2}} \right) \tau_{\mathrm{multi}} + \tau_{\mathrm{static}}$$

where S/N is the desired signal-to-noise ratio, $\mathrm{CR_p}$, $\mathrm{CR_b}$, and $\mathrm{CR_{nf}}$ are the photon count rates of the planet, background, and noise floor, respectively. α parameterizes the point spread function (PSF) subtraction method, and τ_{multi} and τ_{static} are multiplicative and fixed overhead times, respectively, accounting for telescope slew/settling time and achieving the required coronagraphic contrast ratio. Importantly, `pyEDITH` has functionality to calculate S/N given a desired exposure time by inverting the equation above:

$$\mathrm{S/N} = \mathrm{CR_p} \left[\mathrm{CR_{nf}^2} + (\mathrm{CR_p} + \alpha \mathrm{CR_b}) \left(\frac{\tau_{\mathrm{multi}}}{\tau - \tau_{\mathrm{static}}} \right) \right]^{-0.5}$$

Planetary Signal

The count rate of the planetary target is given by:

$$\mathrm{CR_p} = F_\mathrm{p}\ A\ \Upsilon\ T\ \Delta\lambda$$

where F_p is the planet flux $[\frac{\mathrm{photon}}{\mathrm{cm \cdot s \cdot nm}}]$ at the telescope before it proceeds through the instrumentation, A is the collecting area [cm^2], Υ is the fraction of light entering the coronagraph that is within the photometric core of the off-axis (planetary) PSF assuming perfectly transmitting/reflecting optics, T is the total throughput of the optics, and $\Delta\lambda$ is the wavelength bin width [nm].

Background (noise) count rates

The background count rate is composed of stellar leakage, zodiacal/exozodiacal light, observatory thermal radiation, and detector noise, and is given by:

$$\mathrm{CR_b} = \mathrm{CR_{b,*}} + \mathrm{CR_{b,zodi}} + \mathrm{CR_{b,exozodi}} + \mathrm{CR_{b,thermal}} + \mathrm{CR_{b,detector}}$$

Stellar leakage

Coronagraphs cannot block all host star light, and so the stellar leakage term is given by:

$$\mathrm{CR_{b,*}} = F_*(\lambda)\ \zeta\ \Omega\ A\ \Upsilon\ T\ \Delta\lambda$$

where $F_*(\lambda)$ is the stellar flux $[\frac{\mathrm{photon}}{\mathrm{cm \cdot s \cdot nm}}]$ as a function of wavelength, ζ is the contrast suppression factor of the coronagraph, and Ω is the photometric aperture.

[2] https://pyedith.readthedocs.io/en/latest/

Zodiacal dust

The count rate of the solar system zodiacal dust, assumed to be a gray scatterer, is given by:

$$\mathrm{CR}_{\mathrm{b,zodi}} = F_0(\lambda)\ 10^{-0.4z}\Omega\ A\ \Upsilon\ T\ \Delta\lambda$$

where $F_0(\lambda)$ is the zero-point flux $[\frac{\mathrm{photon}}{\mathrm{cm \cdot s \cdot nm}}]$ as a function of wavelength and z is the V-band surface brightness of the zodi $[\mathrm{mag/arcsec^2}]$, scaled by the zodi optical depth integrated along the target line of sight (Leinert et al., 1998).

Exozodiacal dust

The count rate of habitable zone dust in exoplanet systems analogous to the zodiacal light, and is given by:

$$\mathrm{CR}_{\mathrm{b,exozodi}} = F_0(\lambda)\ n10^{-0.4x}\Omega\ A\ \Upsilon\ T\ \Delta\lambda$$

where x is the surface brightness in the V band of the exozodi, assumed to be $22\ \mathrm{mag/arcsec^2}$ and a gray scatterer. n is the exozodi multiplier, which controls the density of exozodiacal dust in a system as a multiple of zodiacal dust.

Thermal background

The thermal emission of the observatory is given by:

$$\mathrm{CR}_{\mathrm{b,thermal}} = \frac{B_\lambda}{E_{\mathrm{photon}}}\ \varepsilon_{\mathrm{warm}}\ T_{\mathrm{cold}}\ \mathrm{QE}\ \Omega\ A\ \Delta\lambda$$

where B_λ is the blackbody function per unit wavelength; E_{photon} is the energy of the photon; $\varepsilon_{\mathrm{warm}}$ is the effective emissivity of all warm optics; T_{cold} is the transmission/reflectivity of all cold optics; QE is the detector's quantum efficiency.

Detector noise

Noise from the detector is given by:

$$\mathrm{CR}_{\mathrm{b,detector}} = N_{\mathrm{pix}}\left(\mathrm{DC} + \frac{\mathrm{RN}^2}{t_{\mathrm{read}}} + \frac{\mathrm{CIC}}{t_{\mathrm{count}}}\right)$$

where N_{pix} is the number of detector pixels in the photometric aperture; DC is the dark current $[e^-/\mathrm{pix/s}]$, RN^2 is the read noise $[e^-/\mathrm{pix/read}]$, t_{read} is the read time [s], CIC is the clock-induced-charge $[e^-/\mathrm{pix/photon}]$; and t_{count} the photon counting time [s].

Noise floor

The noise floor count rate simulates imperfect coronagraphic speckle subtraction and is given by:

$$\mathrm{CR}_{\mathrm{nf}} = \mathrm{CR}_{\mathrm{b},*}/\mathrm{PPF}$$

where PPF is an assumed post-processing factor (nominally 30 for HWO, assuming 10^{-10} raw contrast is achieved) (Nemati et al., 2023).

Imaging mode

In broadband photometry mode, pyEDITH can calculate the exposure time needed to reach the S/N required for initial exoplanet detection surveys in any bandpass for user-defined exoplanet systems (Figure 2). This enables trade studies to determine the set of filters that will maximize the photometric science return of HWO. As a consequence, pyEDITH also allows the study of multi-bandpass photometric strategies, as described in Alei et al. (2025).

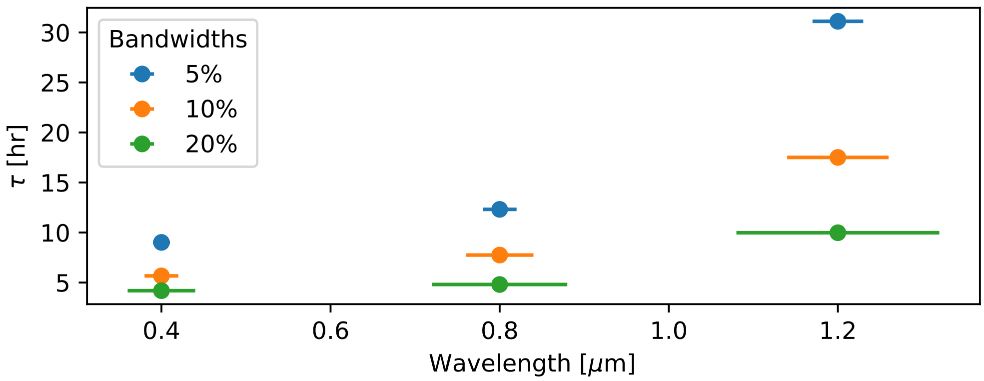

Figure 2: Example of photometric exposure times required to achieve SNR=7 in different bandpasses and bandwidths, assuming an underlying Earth-like spectrum.

Spectroscopy mode

The spectroscopy mode of `pyEDITH` calculates exposure time and S/N as a function of wavelength given user-defined models of the host star and exoplanet reflectance spectra. The user can define spectral channels and their corresponding resolutions, enabling maximum flexibility for spectroscopic instrumentation trade studies; however, we do not consider a line spread function at the time of writing. Finally, `pyEDITH` can synthesize noisy exoplanet observational data to use in precursor data analysis studies (see Figure 3 and Currie et al. (2025)).

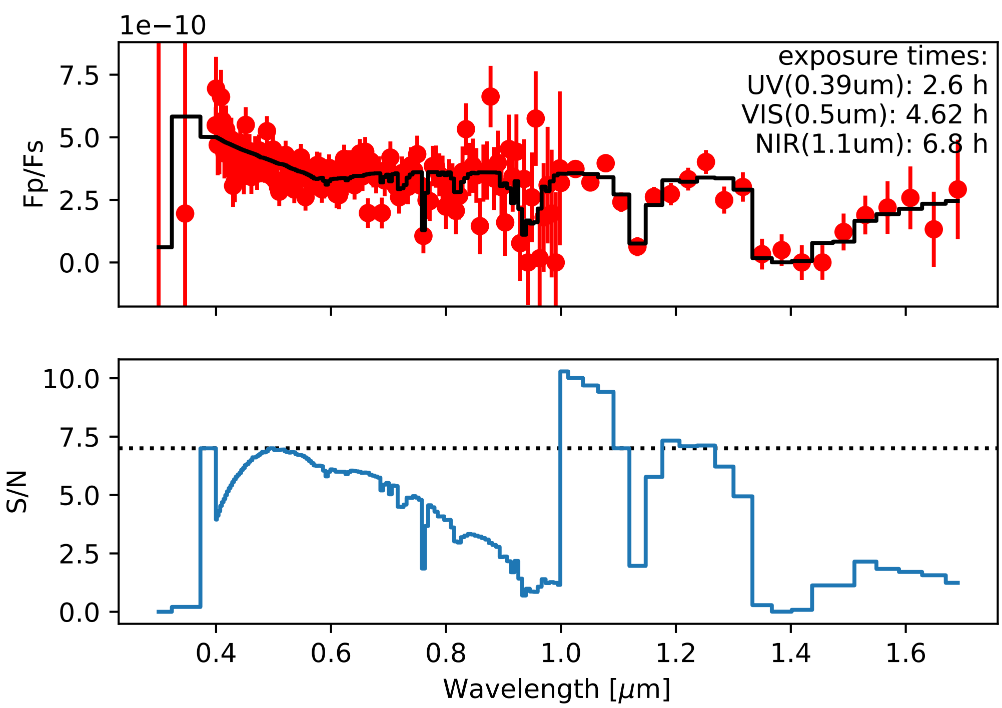

Figure 3: Example of `pyEDITH`-synthesized HWO data (red) of an Earth-like exoplanet (upper) and the calculated S/N as a function of wavelength (lower).

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