JWST Coronagraphy in ETC

The JWST Exposure Time Calculator (ETC) develops and evaluates the complex, multi-source astronomical scenes that are characteristic of JWST high-contrast imaging (HCI).

Introduction

> *Parent article: JWST High-Contrast Imaging*
> *Main articles: JWST ETC Coronagraphy Strategy*

The standard coronagraphic sequence—not yet fully supported by the ETC—will combine two complementary PSF subtraction strategies:

- referenced differential imaging (RDI), which involves subtracting a coronagraphic image of a nearby PSF reference star
- angular differential imaging (ADI), which involves differencing two coronagraphic images of the bright host source that differ only by a telescope roll of ~10°

Thus, when fully implemented, the standard coronagraphic sequence will involve a minimum of three observations:

1. A science observation with the host centered in the coronagraphic mask
2. A second science observation after a telescope roll, with the host centered in the coronagraphic mask
3. A PSF reference observation with the PSF reference star centered in the coronagraphic mask

Adding small grid dithers (SGDs) of the PSF reference star is a future variant of the standard coronagraphic sequence. SGDs can increase the confidence that misalignments between the position of the science PSF and reference PSF relative to the coronagraph masks have a minimal impact on the final contrast.

The example ETC computations below capture the current scope of functionalities for coronagraphy and are limited to only the standard coronagraphic sequence elements 1 and 3, listed above, because the ADI processing is not currently supported by the ETC.

> in the absence of on-sky data, it is hard to predict the PSF stability to the degree that has been achieved with Hubble Space Telescope. As a consequence, until we get data, the ETC does not support either ADI or SGD—only RDI.

In its current implementation, the ETC is mainly useful for two tasks: (1) investigating detector saturation and (2) computing the signal-to-noise ratio (SNR) of a faint companion source under the *ideal contrast* assumption. Ideal contrast is the most optimistic assumption possible because it assumes one type of noise is dominant: the counting statistics of collected photons (shot noise). See Contrast Considerations for JWST High-Contrast Imaging for more information about the "ideal" assumption.

The ETC treats residual flat field noise. The flat field error is a division by ~1 (the flat field is normalized), with a variance of 1/ff_electrons. Note that the value of the flat field response is constant for multiple exposures and multiple integrations, so $N_{exposures} > 1$ does not decrease the residual flat field noise. To reduce it, a user either has to improve the flat field or dither with >1 pixel offsets. The most apparent effect for everyday ETC use is that residual flat field noise sets an upper limit on the achievable SNR.

The SNR source must lie within a square centered on the coronagraphic mask, aligned with detector rows and columns, with sides of 101 pixels for NIRCam or 81 pixels for MIRI.

This article is about ETC functionalities specific to coronagraphy. The reader is encouraged to become acquainted with the general ETC documentation, which covers the underlying algorithms, synthetic astrophysical scenes, simulated JWST exposures, step-by-step ETC operations, and best practices. The reader should take particular cognizance of this article: JWST ETC Coronagraphy Strategy.

Avoiding saturation

In high-contrast imaging (HCI), the host source can be orders of magnitude brighter than the companion source. Therefore, deep coronagraphic exposures call for a large dynamic range, notwithstanding that the coronagraphic mask (occulter) blocks a significant amount of light from the host.

If the exposure time (which involves the number of up-the-ramp, non-destructive reads in an integration), or if the number of groups (N_{groups}) is too large, then saturation will occur, starting with detector pixels close to the image of the coronagraphic mask on the detector.

Because saturation is nonlinear, and because post-observation image processing procedures are based on linear combinations of images, saturation cannot be calibrated away or compensated for by the data pipeline. As a consequence, if faint portions of the circumstellar scene overlap with the saturated pixels, those portions may not be properly detected.

Therefore, saturation is a potential show stopper for programs involving faint features at small apparent separations.

The ETC separately flags pixels that are expected to saturate at some point within a ramp. This feature lets users make subtle distinctions to deal with saturation. For example, if a ramp goes into saturation at, say, N_{groups} = 10, the slope may still be accurately recoverable by discarding from the analysis only the individual frames where saturation has occurred.

The user checks for saturation using the **Saturation** tab in the **Images** pane on the **Calculations** page in the ETC.

In some cases, warnings in the ETC **Reports** panel will indicate whether some ramps may still be useful. The user must proceed by trial and error, varying the readout pattern and N_{groups} until all pixels at the expected position of the companion are not saturated. Note that if at least one pixel in the scene is saturated, the ETC will produce a warning.

PSF subtraction strategy

Currently, the PSF subtraction strategy is called "optimal." The ETC quantifies the shot noise in the wings of either the host or reference sources, as appropriate, at the position of the faint companion source.

The ETC engine is designed to support predictions of coronagraphic performance, including estimates of the PSF using one or multiple reference images. The **Strategy** tab of the GUI calls for choices of reference target and PSF calibration method. Nevertheless, as discussed in JWST Coronagraphic Observation Planning and JWST Coronagraphic Sequences, until calibration programs have quantified the on-orbit stability of the optics, it will be difficult to quantify the expected performance of the various options for PSF subtraction, and therefore, to estimate the limiting contrast*(C_{limit})*. As a consequence, we direct the user to the WebbPSF tool, discussions of limiting contrast, and details on how to design a coronagraphic sequence.

Note that even when higher fidelity statistical models of the PSF are available, limiting contrast will always ultimately be limited by the accuracy of the PSF subtraction, rather than on photon statistics and the actual exposure time. Because limiting performance is controlled by systematic effects—fluctuations in the observatory optics between exposures—doubling or tripling the exposure time won't help.

On the other hand, if the stability time of the optics is longer than the total duration of the observations—the sum of all exposure times and overheads—then the calibration is said to be "ideal," and the residual noise may be solely controlled by shot noise in the wings of the host and reference sources.

The ETC computes the SNR at that position, and the user can proceed iteratively by increasing or decreasing exposure time until the SNR is acceptable. The related user inputs to the ETC are the number of groups, integrations, and exposures: N_{groups}, N_{int}, and N_{exp}. These three numbers set the total exposure time on the source.

Since March 2018 (patch release ETC 1.2.2), users can download the "Unsubtracted Science Scene" or the "PSF Subtraction Source only" as well as perform sub-optimal subtractions as described in the JWST ETC Coronagraphy Strategy page. The image registration, treatment of the noise and background have not changed and are somewhat optimistic.

The next section provides an example of ETC calculations under the "ideal" assumption.

Example of ETC calculations for high-contrast imaging

Tables A–D show the input values and computational results for an ETC study of an analog of the β Pictoris system, comprising a circumstellar disk and a self-luminous planetary companion. These observations use the MIRI four-quadrant phase mask (4QPM) coronagraph that is optimized at λ_0 = 11.3 μ.

For PSF subtraction in this example, only referenced differential imaging (RDI) is used, with a PSF reference star at an apparent separation significantly larger than that of the host and companion sources.

In Tables A–C, the column headers identify the suite of ETC inputs for coronagraphic observations, presented here in approximately the same order as the user encounters them on the ETC interface.

The column footers, in italics, assign an ordinal label to each input, to facilitate the descriptions and comments.

This section assumes some user familiarity with the general ETC documentation.

Web users may click on Tables A–D for a larger view.

Table A. Sources

Source	Name	Continuum		Normalization		Shape			Offset		
		System	Sp/Teff	Bandpass	Brightness	Type	A+	A–	X	Y	PA
1	star	Phoenix	A5V	Bessel K	3.5 Vega	point	n/a		0	0	n/a
2	disk				4 Vega	extended	1″	2″	0	0	45°
3	reference				3.5 Vega	point	n/a		10″	10″	n/a
4	planet	BB	1700°		15 Vega	point			–1″	–2″	
A1	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*		*A9*	*A10*	*A11*

Table A is a list of notional values of ETC input parameters for four sources: (1) a main sequence star that is the “host,” (2) a circumstellar disk centered on the host, (3) a PSF reference star, and (4) a self-luminous planetary companion.

A1–A2: source identifiers
A3–A4: the spectrum or color of a source, expressed as a spectral type in the Phoenix system or as the effective temperature (T_{eff}) of a blackbody (BB)
A5–A6: the apparent Vega magnitude of the source in K band. Note that, for now, the value of the brightness of the reference star must be identical to the value for the host star. Otherwise the ETC will give unphysical negative SNRs
A7–A8: the shape of each source, point or extended. If extended—referring now to the disk—*A8* gives the standard deviations (A+, A–) of an equivalent dual-Gaussian distribution
A9–A11: the X and Y offsets of a source from (0,0), and the rotation-in-place of the source (not meaningful for point sources)

The information on the host and reference stars comes from a catalog or outside research.

The X-Y offsets and PA value are arbitrary and purely notional.

Table B. Calculations

Calculations		Background			Setup		Detector				
Calculation #	Sources	RA/Dec	Level	Date	Coronagraph	Filter	Subarray	Pattern	Groups	Integrations	Exposures
1	1, 3, 4	0/0	low	any	FQPM	F1065C	M1065	fast	10	60	10
2	1, 2, 3					″					
B1	*B2*	*B3*	*B4*	*B5*	*B6*	*B7*	*B8*	*B9*	*B10*	*B11*	*B12*

Tables B and C set up the "scenes" of sources for each calculation—here are two of them—and specifies the instrumental and observational parameters and procedures.

B1: calculation identifier
B2: sources included in the scene
B3–B5: zodiacal light foreground (ignored)
B6–B7: instrument setup (selected coronagraph type and filter)
B8: detector subarray
B9–B12: detector readout pattern and numbers of groups, integrations, and exposures

Table C. Strategies

Strategy								
Observation			Extraction					
Scene rotation	PSF sub source	PSF subtraction	SNR source	Contrast azimuth	Aperture rad	Contrast separation	Sky annulus	
							Inner	Outer
0	3	optimal	4	45°	0.3″	1″	0.45″	0.7″
	″		2				″	
C1	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*

C1: "scene rotation" is an angle theta that:

- rotates the position of a point source by theta
- rotates the position and orientation of an extended sources (although generally they are centered at 0 0)

C2: select the reference source, selecting a source identifier from *A1*. Here, with only the RDI PSF strategy available, we must choose source #3
C3: only "optimal" PSF subtraction is currently available
C4: select which companion source is being observed (disk or planet)
C5: "contrast azimuth" is

1. The azimuthal direction along which the contrast vs separation figure is produced
2. The azimuthal direction used for the scalar calculation of contrast in the text form ETC report

C6: radius of the virtual photometric aperture, which is centered on the position of the SNR source
C7: "contrast separation" is the radial separation used for the scalar calculation of contrast in the text form ETC report
C8–C9: specify the annular, virtual photometric aperture, which collects stray light from around the SNR source, preparing for its subtraction in post-processing

Table D. Parameters and results

Quantity	Computation 1	Computation 2	
Instrument filter/disperser	f1065c/null		*D1*
Extraction aperture position (arcsec)	[–1.00, –2.00]	[0.00, 0.00]	*D2*
Wavelength of interest used to calculate scalar values (microns)	10.55		*D3*
Size of extraction aperture (arcsec)	0.3		*D4*
Total time required for strategy (seconds)	2880.00		*D5*
Total exposure time (seconds)	1440.00		*D6*
Extracted flux (e^-/sec)	285.24	101.25	*D7*
Standard deviation in extracted flux (e^-/sec)	7.48	13.54	*D8*
Extracted signal-to-noise ratio	38.13	7.48	*D9*
Input background surface brightness (MJy/sr)	20.71		*D10*
Total background flux in extraction aperture (e^-/sec)	1419.98	11894.21	*D11*
Total sky background flux in extraction aperture (e^-/sec)	909.99	909.20	*D12*
Fraction of total background flux due to signal from scene	0.36	0.92	*D13*
Average number of cosmic rays per ramp	3.7×10^{-4}		*D14*
Radius at which contrast is measured (arcsec). Same as *C7*	1.0		*D15*
Azimuth at which contrast is measured (degrees). Same as *C5*	45.0		*D16*
Contrast	see Figure 3		*D17*

Table D gives the values of parameters and results summarized in the **Reports** pane of the **Computations** tab.

Discussion

The ETC output plots show no evidence of saturation for these computations.

The results of computations 1 and 2—planet and disk—show a reasonable job of detecting both the planet and disk, with SNR = 38 and SNR = 7, respectively, in 1,440 s exposure time. See Figures 1 and 2 for the two-dimensional images on the detector.

Figure 1. Detector image for computation 1 (planetary companion)

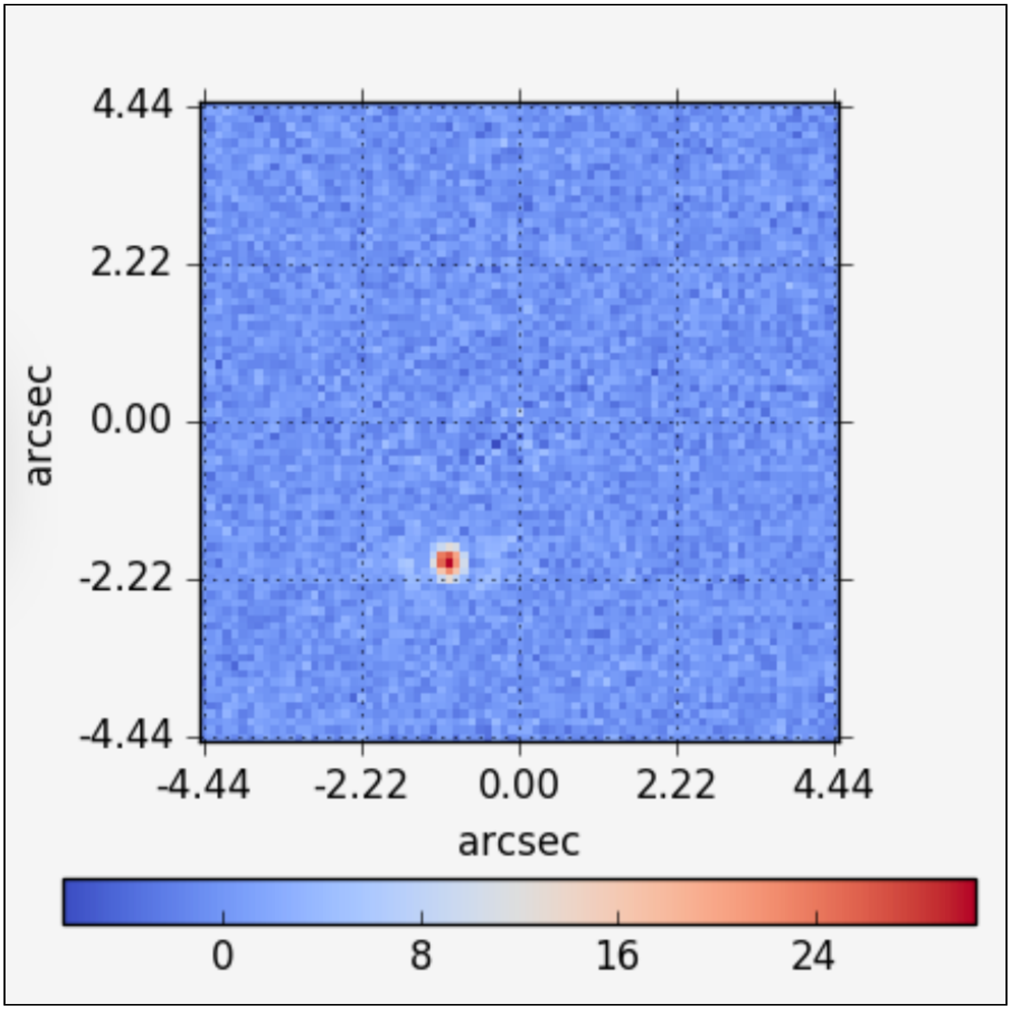


Figure 2. Detector image for computation 2 (circumstellar disk)

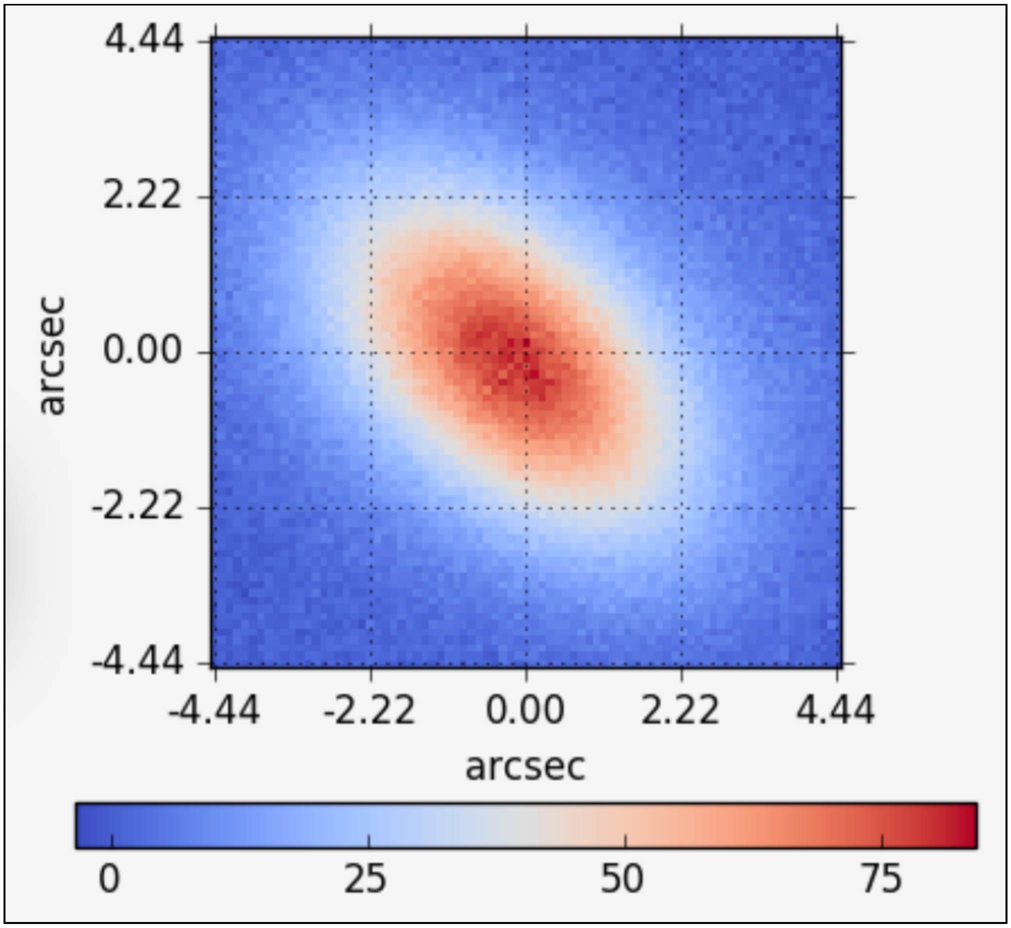
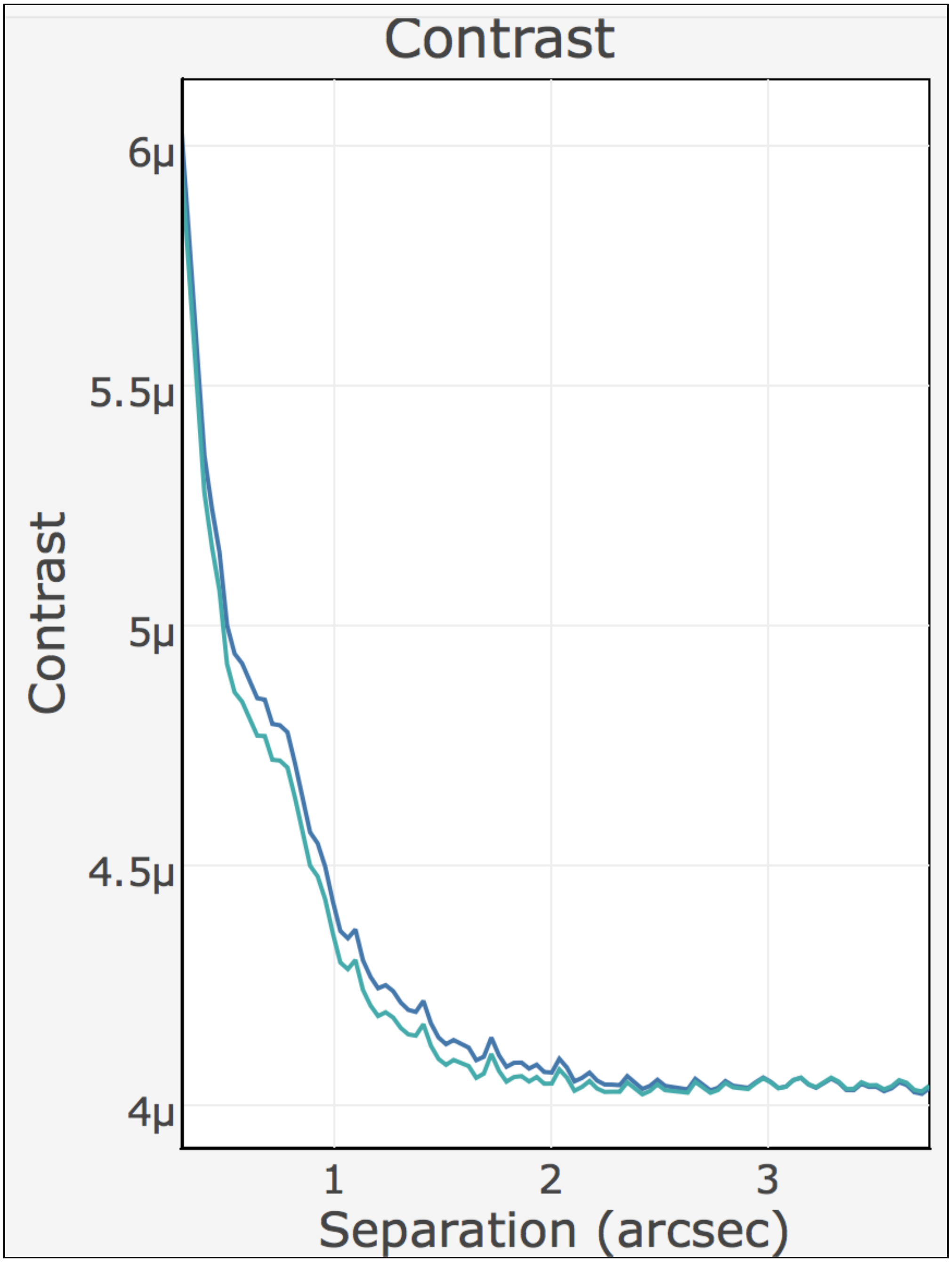


Figure 3 shows the contrast curves for computations 1 and 2, as a function of apparent separation and averaged over azimuth.

Figure 3. Contrast plots for computations 1 (blue) and 2 (green)



The symbol stands for 10^{-6} (dimensionless).