CM Foreword
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## STScI JWST Document Change Record

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1 Abstract
For most coronagraphic observations, the largest term in the noise budget is associated with systematic errors that do not average out when the integration time increases (or when multiple images are co-added). As a consequence, in most cases, these systematic errors (also called speckles) need to be subtracted from the science exposure in order to improve the SNR of the sources observed (often very off-axis when compared to the parent source under the coronagraphic mask). This means that observers need to obtain calibration images (usually called “reference” images) to subtract systematics from the science images. This in turns drives a series of specific use-cases, which have to be taken into account when designing the observation planning and support tools (Astronomer’s Planning Tool, APT, Exposure Time Calculator, ETC, coronagraph pipeline). In a separate white paper the JWST Coronagraph Working Group (JWST CWG) defined the scope of coronagraphic observation sequences from an APT standpoint. This document focuses on the required Exposure Time Calculator functionalities associated with this observing mode with the goal to provide a description of the coronagraphs user needs.

1.1 Reference Documents
Lajoie, C-P, Soummer, R., & Hines D. et al 2013, Simulations of MIRI Four-Quadrant Phase Mask Coronagraph (III): Target Acquisition and CCC mechanism use. STScI JWST Technical Reports JWST-STScI-003546
Lajoie, C-P, Soummer, R., & Hines D. 2013, Simulations of Target Acquisition with MIRI Four-Quadrant Phase Mask Coronagraph (II). STScI JWST Technical Reports JWST-STScI-003065
Soummer, R. & Makidon, R. 2010, Simulations of MIRI Coronagraphic Images. STScI JWST Technical Reports JWST-STScI-001952
Soummer, R. & Makidon, R. 2010, Simulations of MIRI Coronagraphic Images. STScI JWST Technical Reports JWST-STScI-001952
Pontoppidan, K. et al. 2011, ETC algorithms
Mawet, D. et al., Fundamental limitation of high contrast imaging at small angles set by small samples statistics, Submitted to ApJ
2 Scope of user needs for a coronagraphic ETC

2.1 Context

The purpose of the ETC (Exposure Time Calculator) is to provide the observer with the information necessary to design a proposal that will yield successful observations. By successful we mean that the astronomical observables sought by a given program will be accessible at the level of SNR required to carry out the scientific interpretation of the data. For most observing modes, the ETC focuses on simulating the properties of science exposures, assuming that detector level instrumental properties (dark current, residual flat field errors, etc.) are assumed common for all exposures. On the contrary when using the coronagraphs it is critical to obtain a good science exposure and one good reference Point Spread Function (PSF) that matches the science PSF. There are numerous recipes to obtain an adequate reference PSF associated with a given science exposure. Preferred strategies vary significantly from observer to observer and science case to science case. The CWG acknowledges that is not the role of the ETC to tell the observer which sequence of PSF calibration observations will provide an optimal reference PSF. However the ETC is the perfect platform present a visualization of the expected performances for a few significant speckle calibration strategies, in addition to the other more classical sources of noise associated with imaging. Finally because of the various sources of noise in coronagraphic observations, users would greatly benefit from having the results of a given calculation displayed in an error budget format. We have identified five high-level user needs that fit into the spirit of such an error budget approach. Each section of this document is devoted to one of these user needs, with the last section summarizing a wish list of interfaces necessary in order to fulfill these user needs. In an appendix we detail the algorithms associated with speckle noise.

2.2 Definitions

We denote by “off-axis source” any astrophysical object that is the purpose of the coronagraphic observation: off-axis substellar companion orbiting a nearby star, off-axis resolved disk structure orbiting a nearby star, off-axis resolved structure surrounding a distant active galactic nuclei (AGN). Note that the “off-axis source” can be either a single astrophysical object or an ensemble of astrophysical objects associated with a single “ occulted source”.

We denote by “occulted source” the astrophysical object that is placed behind the coronagraph focal plane mask and whose photometric contribution from diffracted light we seek to minimize at the location of the “off-axis source”.

We denote by “telescope state” a unique realization of observatory, telescope, and instrument environmental variables that lead to a unique PSF (OTE, Target Acquisition).

We denote by “ensemble of calibration exposures” the ensemble of exposures from which the PSF reference is built (in the case of single roll subtraction this is just the exposure in the other roll, in the case of a PSF library it corresponds to all exposures in the library).

We denote by “reference PSF” a coronagraphic image, or a combination of such images, that is subtracted from the science exposure in order to remove speckles and enhance off-axis source SNR.
We denote by “raw contrast” the intensity ratio between the occulted source and the speckles (or the residual speckles after PSF subtraction) in the integrated flux density sense. This is the metric used in previous CWG technical reports to predict the performance of the MIRI coronagraphs with respect to various environment variables and detector artifacts.

We denote by “detection limit” the ability to distinguish a off-axis astrophysical source from speckles (or residual speckles after PSF subtraction) at a given level of statistical significance. This means that the user chooses a level of statistical significance, for instance 3 sigma, and the ETC provides the faintest brightness for the off-axis source that case be detected at that 3 sigma level. While related to the raw contrast, the detection limit assumes that a signal extraction algorithm is applied to the coronagraphic image and is based on the signal to noise ratio derived using that algorithm. It is the main scientific metric of interest when planning coronagraph surveys.

2.3 Overview of Top-level User Needs
The needs for the coronagraphic ETC are organized in five User Needs summarized below and in the following sections. Unless specified, the CWG has identified that these functionalities are “must have” for the ETC.

[UN.1] Standard imaging ETC:
The ETC must quantify the magnitude of all sources of noise except speckle noise, which is specifically addressed in other requirements. This includes photon noise, detector noise, and background noise. For the coronagraphic ETC it is necessary that all tools of regular imaging are available AND can be used on simulated off-axis astrophysical sources, such as point sources (e.g. planets). Note that some coronagraph throughput components are not included with regular imagers (including FPM and Lyot Stop throughputs, none of these elements are field dependent).

[UN.2] PSF and detector geometry (saturation, spiders, focal plane mask geometry):
The ETC must take into account the effects of regions of the PSF for which speckle suppression is more difficult (saturation, spiders, focal plane mask geometry, e.g. edges of the 4QPM or NIRCam wedges), or the off-axis source throughput is low. The ETC must be able to quantify these effects.

[UN.3] Contrast in the raw coronagraphic data:
The ETC must quantify the level of speckle noise prior to PSF subtraction. This corresponds to the worst-case scenario (no PSF subtraction).

[UN.4] Photon noise on speckles:
The ETC must quantify the level of residual photon noise in the hypothetical case that the PSF subtraction is perfect. This corresponds to the best-case scenario.

[UN.5] Contrast after PSF-subtraction:
The ETC must quantify the level of residual speckle noise in a few representative cases of speckle calibration strategies (using a few representative cases of reference PSF obtained using a few representative cases of observation sequences). Depending on the observing
strategy this can include several options, from a “classical PSF subtraction”, to a more advanced subtraction based on a PSF library. The result of this calculation is bound between the two cases described in UN.3 and UN.4.

In section 3 to 7 of this technical report we describe the functionalities that are associated with each of these top-level user needs.
3 User Need #1: Standard imaging ETC

[UN1.1] Speckle free off-axis source SNR given an exposure time

Statement:
For a given exposure specification and a given astrophysical off-axis source, the ETC can calculate the SNR for the source in the absence of speckles (e.g., shot noise from the source, estimate background and detector noises).

Desired Inputs:
1. Description of the off-axis source astrophysical properties.
2. Location of the off-axis source on the detector (in angular units, arcseconds)
3. Instrument setup.
4. Total exposure time.
5. Signal extraction algorithm.

Desired Outputs:

Suggested Methods:
1. Same methods as the regular imaging ETC, including photometric efficiency associated with dithers recombination (if small-grid Fast Steering Mirror, FSM, dithers are used). Note that the Lyot stop throughputs and the Focal Plane Masks off-axis throughputs have to be included. This applies for all user needs where post-coronagraph signal ought to be calculated, namely UN. 1.2, 1.3, 3.1, 3.2, 4.1 and 4.2. Indeed, the off-axis response of the coronagraphs changes as a function of field point both radially (distance from the focal plane mask) and azimuthally (for the NIRCAM wedge occulters and the MIRI Four Quadrant Phase Masks). Because the throughput loss is very severe for the latter cases, specific user needs leading up to warnings are described in this document (2.3 and 2.4).
2. In general the off-axis response for a single field point can be calculated by the Webb PSF tool and tabulated in an off-axis PSF library (see Section 8: Interfaces). Each field point in the astrophysical scene can then be “convolved” to this PSF library. While this calculation is straightforward in the case of a off-axis point sources it can become complicated when considering extended off-axis sources such as circumstellar disks. Because the coronagraph response is field dependent classical convolution, cannot be carried out and the direct integral has to be evaluated. This can translate into significant calculation overheads that might have to be quantified before ETC implementation (see later discussion regarding off-axis PSF library).

[UN1.2] Speckle free exposure time to reach a given SNR for the off-axis source

Statement:
For a given target SNR and a given astrophysical off-axis source, the ETC can calculate the minimum exposure time for the source in the absence of speckles (e.g., shot noise from the source, estimate background and detector noises).

Desired Inputs:
1. Description of the off-axis source astrophysical properties: spectrum, magnitude, and surface brightness.
2. Location of the off-axis source on the detector (location in pixels).
3. Instrument setup.
4. Target SNR.
5. Signal extraction algorithm.

**Desired Outputs:**
1. Minimal exposure times to reach target SNR associated with read, background, and photon noise on the off-axis source.
2. Overall “speckle free” exposure time to reach target SNR.

**Suggested Methods:**
1. Same methods as the regular imaging ETC, including photometric efficiency associated with dithers recombination (if small-grid FSM dithers are used). Note that the Lyot stop throughputs and the Focal Plane Masks off-axis throughputs have to be included.

[UN1.3] **Speckle free detection limit**

**Statement:**
For a given exposure time and a given target SNR the ETC can calculate the detection limit for the source in the absence of speckles (e.g. estimate background and detector noises).

**Desired Inputs:**
1. Target SNR (statistical significance of detection), input value
2. Instrument setup.
3. Total exposure time.
4. Signal extraction algorithm.

**Desired Outputs:**
1. 2D detection limit: magnitude of faintest point source that can be detected with the statistical significance set by the Target SNR and the total exposure time.
2. 1D detection limit: magnitude of faintest point source that can be detected with the statistical significance set by the Target SNR and the total exposure time as a function of angular separation.

**Suggested Methods:**
1. Same methods as the regular imaging ETC, including photometric efficiency associated with dithers recombination (if small-grid FSM dithers are used). Note that the Lyot stop throughputs and the Focal Plane Masks off-axis throughputs have to be included.
4 User Need #2: Detector and coronagraph geometry

Figure 4-1 illustrates the various user needs identified in this section (from Krist et al. 2007). In this figure, generated for the NIRCAM coronagraphic wedge at F460M we have identified the portions of the PSF where the detectability of off-axis sources can be hampered by the presence of the telescope’s spiders. Other sources of asymmetries can yield to loss of detectability in coronagraphic PSF: more severe loss of off-axis throughput related to a thicker focal plane occulter or in the quadrant’s edges for the MIRI coronagraphs. In this section we denote these zones of the focal plane (even if they are stemming from different phenomena) as “asymmetric coronagraphic PSF structures”.

![Full exposure diagram]

Figure 4-1 Illustration of the user needs regarding the PSF structures. The full exposure time is divided in a suite of up the ramp in order to ensure that the core of the PSF is not saturated beyond a central disk (indicated in red). The ETC is able to determine the up the ramp time for a given radius (alternatively for a given up the ramp time the ETC is able to calculate this radius). Moreover the ETC provides a warning if the off-axis source is at a position angle that places it in the saturated region or under the coronagraph PSF asymmetric structure (NIRCAM coronagraphic wedge in this example).
[UN3.1] Saturation radius for a given up the ramp time

**Statement:**
For a given occulted source geometry and a given up the ramp time (always shorter than the minimal exposure time derived above, see Figure 4-1) the ETC will calculate the largest separation (both in pixels and arcsec) at which the PSF will saturate. Saturation is here defined by the saturation in at the final group of the ramp (the PSF might not me saturated at intermediate groups in the ramp, but these “sub-exposures” are in general not sensitive to the off-axis source.

**Desired Inputs:**
1. Description of the occulted source astrophysical properties.
2. Location of the off-axis source in the detector (location on sky).
3. Instrument setup
4. Up the ramp time.

**Desired Outputs:**
1. 2D image with pixels shown as on/off depending on saturation.
2. 2D PSF with saturated pixels clearly identified, and overlaid with the location of the off-axis source.
3. Warning if the PSF is saturated at the location of the off-axis source.
4. Largest separation (both in pixels and arcsec) at which the PSF will saturate.
5. Largest separation (both in pixels and arcsec) at which the PSF will saturate over a 360 degrees field of view (e.g. do not take into account pixels for which spiders or asymmetric coronagraphic PSF structures are saturated).

**Suggested Methods:**
1. Use a template coronographic PSF corresponding to the instrument set-up. Based on this PSF profile and the properties of the occulted source properties determine the ensemble of pixels that are saturated.

[UN3.2] Exposure time for an azimuthally symmetric saturation zone

**Statement:**
For a given occulted source geometry and a given maximum separation (both in pixels and arcsec) at which the PSF ought to saturate, the ETC can calculate the maximum allowable up the ramp time.

**Desired Inputs:**
1. Description of the occulted source astrophysical properties.
2. Location of the off-axis source in the detector (list of pixels or location on sky).
3. Instrument setup
4. Largest separation (both in pixels and arcsec) at which the observer is comfortable having the PSF saturating over the entire 360 degree Field Of view.

**Desired Outputs:**
1. Maximum allowable up the ramp time.
2. 2D image with pixels shown as on/off depending on
3. for this maximum allowable up the ramp.
4. 2D PSF with saturated pixels clearly identified, and overlaid with the location of the off-axis source for this maximum allowable up the ramp time.

**Suggested Methods:**

1. Use a template PSF corresponding to the instrument set-up. Based on this PSF profile and the properties of the occulted source calculate which up the ramp time corresponds to the largest separation at which the PSF ought to saturate over the entire 360 degrees FOV.

[UN3.3] **Location of off-axis source with respect to coronagraphic PSF structures**

**Statement:**

For a given off-axis source on-sky geometry and a given telescope roll angle, the ETC can identify the location of the off-axis source signal with respect to the coronagraphic PSF structures (spiders, coronagraphic bar, quadrant edges of the FQPM). Note that in this scenario the ETC ought to know the relative orientation of the detector with respect to the sky, but not the range of schedulable roll angles. Should this information not be available in the ETC, the user will then choose the telescope orientation using either an auxiliary tool or the coronagraph documentation.

**Desired Inputs:**

1. Description of the occulted source astrophysical properties.
2. Location of the off-axis source on sky.
3. Instrument setup
4. Telescope roll angle.

**Desired Outputs:**

1. 2D PSF with asymmetric coronagraphic PSF structures clearly indicated, overlaid with the location of the off-axis source in the focal plane array for the chosen roll angle. Note that this is not a noise calculation but rather a visualization of the geometry of the Field Of View. While traditionally this type of visualization is implanted in APT the CWG recommends that it is accommodated within the ETC in order to keep all calculations within the same tool.
2. Warning if the off-axis source is located under these structures.

**Suggested Methods:**

1. Use a template PSF corresponding to the instrument set-up. Based on this PSF profile, the on Sky location of the off-axis source on the detector and the telescope roll angle generate the desired outputs.

[UN3.4] **Range of roll angles, preventing off-axis source/PSF structures overlap.**

The CWG identified this user need is a “want” and not a “must have”. If not implemented the information necessary to conduct this calculation will be located in the coronagraphic observations documentation.

**Statement:**
For a given off-axis source on-sky geometry the ETC will be able to determine the ranges of the telescope roll angle for which the source image is not located being behind the coronographic PSF structures (spiders, coronagraphic bar, quadrant edges of the FQPM).

**Inputs:**
1. Description of the occulted source astrophysical properties.
2. Location of the off-axis source on sky.
3. Instrument setup.
4. Table of coronagraphic PSF structures (spiders, coronagraphic bar, quadrant edges of the FQPM) on-sky location as a function of roll angle.

**Outputs:**
1. 2D PSF with asymmetric PSF structures clearly indicated, overlaid with the location of the off-axis source in the focal plane array for the chosen roll angle.
2. List of roll angles for which the off-axis source is not behind under the coronagraphic PSF structures (spiders, coronagraphic bar, quadrant edges of the FQPM).

**Suggested Methods:**
1. Load the table of coronagraphic PSF structures (spiders, coronagraphic bar, quadrant edges of the FQPM) on-sky location as a function of roll angle. Based on off-axis source on-sky geometry calculate the list of admissible roll angles.
The three sources of noise in the error budget are indicated: raw contrast, single reference subtraction and fundamental limit set by the photon noise. The ETC user is able to fill this diagram with these various noise sources of plus the ones calculated by the direct imaging ETC and is able to combine them for a global representation of the detection limits accounting for all noises (including classical imaging sources of noise).

Figure 4-2 Mock up of the a desired the 1D ETC report on speckle noise based on MIRI FQPM+F1140C simulations
5 User Need #3: Speckle noise in the raw coronagraphic data (worse case configuration).

Sections 5, 6, 7 discuss the case of the speckle noise. An example of the final ETC report regarding speckle noise is given on Figure 4-2, which recaps the three terms detail in these sections in the case of MIRI FQPM + F1140 observations. Appendix A articulates how the noise calculation methods, which are compliant with the current Scamp implementation, compare with the tools currently used by the high-contrast imaging community to quantify coronagraph sensitivity limits. Examples of the 2D speckle noise report for each one of these terms are shown in Figure 5-1. On this Figure we introduced synthetic companions at 1’’ and 2.8’’ with brightness such that they would appear by eye inspection at SNR ~1 in the raw PSF, without any subtraction. Putting this in perspective with Figure 4-2, where the same sources are denoted by the red and blue dots respectively, we conclude that methods compliant with the current SCAMP implementation are robust estimates of point sources SNR. We leave the case of extended objects to future work.

[UN3.1] Speckle noise, Signal to Noise ratio.

Statement:
For a given telescope state, a given instrument configuration, and a given off-axis astrophysical source the ETC is able calculate the raw speckle noise in the science exposures. The SNR calculation is based on the PSF of the occulted source and on the image of the off-axis astrophysical source.

Desired Inputs:
1. Description of the occulted source astrophysical properties.
2. Description of the off-axis source astrophysical properties.
3. Off-axis source location in pixels.
4. Telescope state.
5. Observation strategy (coefficient to estimate signal).

Desired Outputs:
1. Estimated SNR for the off-axis astrophysical source.

Suggested Methods:
1. Based on the telescope state and the occulted source astrophysical properties find the adequate correlation matrix in the correlation matrix library.
2. Based on the observation strategy define the coefficients to be used in order to calculate signal.
3. Based on the off-axis PSF library estimate the PSF of the off-axis source and the signal extraction coefficients calculate the signal of the off-axis source. Note that for extended off-axis sources taking into account the actual off-axis through put could to be done either using the look up table described above instead or carrying out a full convolution, as described in UN 1.1.
4. Use the same coefficients in conjunction with the correlation matrix to calculate speckle noise at each point in the field of view.
5. Calculate SNR for off-axis source.
When the reference image is the source itself at a different roll angle then residual noise resulting from sky background subtraction is the same as in classic can imaging (UN 1.1). However when using a calibrator star as a PSF reference there might be sky background variations depending on the sky location between science and reference coronagraphic images. Most nearby JWST exoplanet and disk targets will have K mags between 3 and 7, which based on astrometry in the 2MASS All-Sky Point Source Catalog will translate into an average slew distances of ~1 degree and ~10 arcmin, respectively. While for NIRCam, the slew distances will likely be larger because of the additional constraint of matching spectral types/color we do not expect them to exceed 10 degrees. Thus in most case sky background variations are not a concern. However this might not be the case in the special configuration of the large surveys for which each science target is a potential calibrator. The CWG is currently investigating how prevalent and severe this case might be and suggests implementing ETC calculations without sky background variations for the time being (leaving the possibility for latter updates if possible, in that case the main implementation consequence of this is that the reference star does not need to have an RA/DEC associated with it).

Figure 5-1 Mock up of the a desired the 2D ETC report on speckle noise based on MIRI FQPM+F1140C simulations .The three sources of noise in the error budget are indicated. Synthetic point sources have been inserted in this data at 1'' and 2.8''. Their brightness is consistent with the red and blue dots on Figure 4-2. Top Left: raw contrast. Top Right: single reference subtraction. Bottom Left: fundamental limit set by the photon noise. The ETC user is able to toggle between each source of noise in this diagram and is able to combine them for a global representation of the 2D detection limits accounting for all noises (including classical imaging sources of noise).
[UN3.2] **Speckle noise, point source detection limit.**

**Statement:**
For a given telescope state and a given instrument configuration, the ETC is able calculate the raw speckle noise in the science exposures. The noise calculation is solely based on the PSF of the occulted source.

**Desired Inputs:**
1. Description of the occulted source astrophysical properties.
2. Telescope state.
3. Signal extraction strategy (coefficient to estimate signal).
4. Target SNR

**Desired Outputs:**
1. 2D detection limit. The units of the color scale of this 2D map can be chosen by the user: apparent magnitude, F_\lambda or contrast. The statistical significance of the detection limit is an integer input value from SNR = 1 to SNR = 10.
2. 1D detection limit. The units the y-axis can be chosen by the user among apparent magnitude, F_\lambda or contrast. The units the x-axis are arcsec. The statistical significance of the detection limit is an integer input value from from SNR = 1 to SNR = 10.

For the 1D calculations the output can be presented either using three different line lots that the user chooses or using a single line plot with multiple axes. Ideally the user can also toggle between the units of 2D plots, however this features is not critical as long as the option is available for the 1D display.

**Suggested Methods:**
1. Based on the telescope state and the occulted source astrophysical properties find the adequate correlation matrix in the correlation matrix library.
2. Based on the observation strategy define the coefficients to be used in order to calculate signal.

Based on the off-axis PSF library (normalized to a flux similar to the flux of the bright source before the coronagraph), and the signal extraction coefficients estimate the potential signal at all pixels in the field of view. Because the PSFs in this library off axis sources have been propagated through the focal plane occulters/phase masks and through the Lyot stops, this captures field dependent coronagraphic throughput. This step can be turned into a field dependent throughput lookup table if needed (for extended sources using a off-axis PSF library will not work (or it will work but at a very high computation cost). However calculating an approximate filed dependent throughput map, by which the modes of the extended source is multiplied, does work. The results are not exact but might be “close enough” for ETC purposes. The CWG recommends implementing this option.
3.
4. Use the same coefficients in conjunction with the correlation matrix to calculate noise at each point in the field of view.

5. Based on the expected statistical significance of the detection (target SNR), use signal and noise maps to calculate the magnitude of faintest point source that can be detected with the statistical significance set by the Target SNR.
6  User Need #4: Photon noise on speckles (best case configuration).

[UN4.1]  Photon noise on speckles: Signal to Noise Ratio.

*Statement:*
For a given telescope state and a given instrument, the ETC is able calculate the photon noise floor associated with the raw speckle noise in the science/reference exposures. The SNR calculation is based on the PSF of the occulted source and on the purported image of the off-axis astrophysical source.

*Desired Inputs:*
1. Description of the occulted source astrophysical properties.
2. Description of the off-axis source astrophysical properties and location.
3. Telescope state.
4. Observation strategy (coefficient to estimate signal).
5. Exposure time.

*Desired Outputs:*
1. Estimated SNR for the off-axis astrophysical source.

*Suggested Methods:*
1. Find the faintest source in the observation sequence: if all exposure times are equal this source will be driving the photon noise limit. Note that APT will provide the user with a warning if the reference star is substantially fainter than the occulted source, so in most configurations such pathological cases should not make it to the ETC.
2. Based on a PSF from the PSF library that corresponds to telescope state and to the astrophysical properties of the source driving photon noise, use the exposure time to build a co-variance matrix that is zero everywhere except of each diagonal entry, corresponding to the actual counts in a pixel.
3. Based on the observation strategy define the coefficients to be used in order to calculate signal.
4. Based on the off-axis PSF library estimate the PSF of the off-axis source and the signal extraction coefficients calculate the signal of the off-axis source. Note that for extended off-axis sources taking into account the actually of axis through put can be done using the look up table described above instead of carrying our a fill convolution).
5. Use the same coefficients in conjunction with the correlation matrix to calculate noise at each point in the field of view.
6. Calculate SNR for off-axis source.

[UN4.2]  Photon noise on speckles, detection limit

*Statement:*
For a given telescope state and a given instrument, the ETC is able calculate the photon noise floor associated with the raw speckles in the science or reference exposures (which ever start of these two is the fainter and thus has the poorest photon statistics). The noise calculation is solely based on the PSF of the occulted source. This contrast floor is the
fundamental limit of the dynamic range that can be reached, even in the presence of a perfect calibration PSF.

**Desired Inputs:**

1. Description of the occulted source astrophysical properties.
2. Description of the reference source (if any) astrophysical properties.
3. Telescope state.
4. Observation strategy (coefficients to estimate signal).
5. Exposure time.

**Desired Outputs:**

1. 2D detection limit. The units of the color scale of this 2D map can be chosen by the user: apparent magnitude, $F_{\lambda}$ or contrast. The statistical significance of the detection limit is an integer input value from SNR = 1 to SNR = 10.
2. 1D detection limit. The units the y-axis can be chosen by the user among apparent magnitude, $F_{\lambda}$ or contrast. The units the x-axis are arcsec. The statistical significance of the detection limit is an integer input value from SNR = 1 to SNR = 10.

For the 1D calculations the output can be presented either using three different line lots that the user chooses or using a single line plot with multiple axes. Ideally the user can also toggle between the units of 2D plots, however this features is not critical as long as the option is available for the 1D display.

**Suggested Methods:**

1. Find the faintest source in the observation sequence: if all exposure times are equal this source will be driving the photon noise limit. Note that APT will provide the user with a warning if the reference star is substantially fainter than the occulted source, so in most configurations such pathological cases should not make it to the ETC.
2. Based on a PSF from the PSF library that corresponds to the relevant telescope state and to the astrophysical properties of the source driving photon noise, use the exposure time to build a co-variance matrix that is zero everywhere except of each diagonal entry, corresponding to the actual counts in a pixel.
3. Based on the observation strategy define the coefficients to be used in order to calculate signal.
4. Based on the off-axis PSF library (normalized to a flux similar to the flux of the bright source before the coronagraph), and the signal extraction coefficients estimate the signal at pixel in the field of view. Because the PSFs in this library off axis sources have been propagated through the focal plane occulters/phase masks and through the Lyot stops, this captures field dependent coronagraphic throughput. This step can be turned into a field dependent throughput lookup table if needed.
5. Use the same coefficients in conjunction with the correlation matrix to calculate noise at each point in the field of view.
6. Estimate detection limits based on these estimates of signal, noise and expected statistical significance of the detection.
7 User Need #5: residual noise after PSF subtraction (realistic configuration).

There exists a wide variety of ways to reduce coronagraphic data in order to calibrate the systematics induced by quasi-static speckles. This process can be split into two steps: observation method (how the data necessary of the PSF subtraction is acquired) and the data reduction strategy (how the images in the calibration set of exposures are combined to generate a reference PSF). Since this field is rapidly evolving (Lafreniere et al. 2007, Soummer et al. 2012) the CWG chose to suggest an architecture that accommodates for updates. Namely the ETC will offer to observers choices of both observation and data reduction methods associated with their planned observations. Then, depending on this choice the ETC will point towards entries in the correlation matrix library corresponding to this combination of observation and data reduction strategies and execute the detection limit and SNR calculation. This proposed architecture allows implementing any type of PSF subtraction, by choosing a different correlation matrix. The only term in the noise error budget that is dependent on the type of PSF subtraction corresponds to the present user need, and therefore can be fully addressed by an appropriate library of correlation matrix. The CWG has identified as a “first pass” support for the standard observation sequence with single (mean/median) PSF subtraction algorithm. Should more sophisticated reduction strategies be implement in the coronagraphic pipeline, updates to the PSF subtraction strategy will occur in the correlation matrix library accordingly. As a consequence the ETC coronagraphy ought to be able to point towards various correlation matrices, which depend on the user choosing a give PSF subtraction strategy.

The CWG has identified as “must has” for the ETC the following items:

- Support observation strategies associated with the coronagraphic sequence as defined in APT.
- Support PSF subtraction strategies that rely on generating reference PSFs based on a single exposure or on the mean or median of a series of exposures.
- Allow for a few other observation and PSF subtraction strategies to be added to the ETC interface and in the correlation library at a latter stage.

[UN5.1] Residual speckles after subtraction, Signal to Noise ratio

Statement:

For a given telescope state and a given instrument configuration, and a given off-axis astrophysical source the ETC is able calculate the residual speckle noise after subtraction.

Desired Inputs:

1. Description of the occulted source astrophysical properties.
2. Description of the off-axis source astrophysical properties.
3. Location of the off-axis source in pixels.
4. Telescope state.
5. Observation strategy (coefficient to estimate signal).

Desired Outputs:

1. Estimated SNR for the off-axis astrophysical source.
Suggested Methods:

1. Based on the telescope states (at both the science and the reference exposures), the occulted source astrophysical properties and the observation/PSF subtraction strategies, find the adequate correlation matrix in the correlation matrix library.
2. Based on the observation strategy define the coefficients to be used in order to calculate signal.
3. Based on the off-axis PSF library and the signal extraction coefficients, calculate the signal of the off-axis source. Note that for extended off-axis sources taking into account the actually of axis through put can be done using the look up table described above instead of carrying out a full convolution.
4. Use the same coefficients in conjunction with the correlation matrix to calculate noise at each point in the field of view.
5. Calculate SNR for off-axis source.

Residual speckles after subtraction, detection limits.

Statement:
For a given telescope state and a given instrument configuration, the ETC is able to calculate the residual speckle noise after subtraction.

Desired Inputs:

1. Description of the occulted source astrophysical properties.
2. Telescope state.
3. Observation strategy (coefficient to estimate signal).

Desired Outputs:

1. 2D detection limit. The user can choose the units of the color scale of this 2D map: apparent magnitude, F_lambda or contrast. The statistical significance of the detection limit is an integer input value from SNR = 1 to SNR = 10.
2. 1D detection limit. The units the y-axis can be chosen by the user among apparent magnitude, F_lambda or contrast. The units the x-axis are arcsec. The statistical significance of the detection limit is an integer input value from from SNR = 1 to SNR = 10.

For the 1D calculations the output can be presented either using three different line lots that the user chooses or using a single line plot with multiple axes. Ideally the user can also toggle between the units of 2D plots, however this feature is not critical as long as the option is available for the 1D display.

Suggested Methods:

1. Based on the telescope states (at both the science and the reference exposures), the occulted source astrophysical properties find, and the observation/PSF subtraction strategies, find the adequate correlation matrix in the correlation matrix library.
2. Based on the observation strategy define the coefficients to be used in order to calculate signal.
3. Based on the off-axis PSF library (normalized to a flux similar to the flux of the bright source before the coronagraph), and the signal extraction coefficients
estimate the signal at each pixel in the field of view. Because the PSFs in this library off axis sources have been propagated through the focal plane occulters/phase masks and through the Lyot stops, this captures field dependent coronagraphic throughput. This step can be turned into a field dependent throughput lookup table if needed.

4. Use the same coefficients in conjunction with the correlation matrix to calculate noise at each point in the field of view.

5. Estimate detection limits based on these estimates of signal, noise and expected statistical significance of the detection.
8 Interfaces
In this section we summarize how the user needs described above impact the ETC interfaces. We identified three types of interfaces:

Interfaces with other observation planning tools, namely: APT, the PSF libraries, and the correlation matrices libraries.

Internal interfaces: user needs described above will translate into bookkeeping functionalities for the ETC.

8.1 User interfaces.
Figure 8-1 describes how the user needs translate into additional interfaces and bookkeeping. It emphasizes the potential modifications from the baseline ETC structure. Below we detail these features.

![Figure 8-1 Suggested changes to the ETC architecture to accommodate for coronography. When compared to REF the extra desired functionalities are: interfacing with PSF and correlation libraries, bookkeeping of the various types of sources, and include the PSF subtraction strategy as a parameter in the correlation library.](image)

8.2 Interfaces with other observation planning tools.

8.2.1 APT
The observing sequence is defined in APT, and in particular the sky coordinates of the science and reference PSFs. These will drive the OTE change between observations and will be a significant part of the variations of telescope/instrument state between science and reference exposure (as well as Target Acquisition, which will also result from entries in APT). The magnitude of such variations will have to be calibrated during commissioning activities. The CWG suggests to develop ETC and the PSF library in a

Check with the JWST SOCCER Database at: [https://soccer.stsci.edu](https://soccer.stsci.edu)
To verify that this is the current version.
way that will accommodate for future updates of the relationship between pointing maneuvers, Target Acquisition and range of variations of the telescope/instrument state.

8.2.2 PSF library

The PSF library will be composed of the ensemble of simulated PSFs that are necessary for the SNR calculation. Note that here we are loosely using the term library: in practice instead of storing all the PSFs associated to each telescope/instrument state one could calculate them on the fly. The CWG does not favor one option over the other and suggests that a detailed traded of study between storage volume/memory access resources and computational time should be carried out. A final decision ought to be made as a result of this study. Note however that coronagraph simulations might be somewhat more demanding computationally than regular imaging simulations since they require a series of Fourier transform type operations. We suggest that the PSFs in the libraries be to normalized to one photon entering the JWST primary and that scaling to a given source magnitude be done as a function of the astrophysical properties of the occulted source.

There are two types of PSF libraries:

- Off-axis PSF library, which encompasses variations in flux and morphology of the coronagraphs’ PSF as a function of field point. This captures the throughput of the instrument with respect to source position in the coronagraphic field. It is necessary to the ETC estimate of the signal of the off-axis source. Should this component deem to be too computationally /memory expensive it can be replaced by a lookup table of throughput as a function of field position (and is the only tractable solution for extended sources). Note that telescope/instrument state only has a minor impact on this type of PSFs and thus it is not necessary include such variations in the off-axis library.

- Occulted PSF library that captures the PSF of the instrument for a finite (albeit large) and representative ensemble pixel list of telescope/instrument states.
8.2.3 Correlation Matrix library

Figure 8-2 Suggested decision tree to pick a given correlation matrix to estimate the noise term associated with speckles.

Most entries regarding the bright source and the references are chosen by the ETC user. In turn these entries are fed to look up tables (to be calibrated during commissioning activities) that translate the observation sequence into a telescope/instrument state variables relevant to coronagraphy. Based on these and on the PSF subtraction strategy chosen by the user the adequate correlation matrix is chosen to estimate the noise in the coronagraphic exposure.

The correlation matrix library will be the main resource to estimate speckle noise in coronagraph observations. Here again we use library in the loose sense as correlation matrices could be calculated on the fly from based on the PSF library. The CWG does not favor one option over the other and suggests that a detailed trade study between storage volume/memory access resources and computational time should be carried out. A final decision ought to be made as a result of this study. Note however that the memory requirement might also be loosened using sparse matrices (under that assumption pixels in opposites sides of the filed of view are not correlated). Moreover, as also mentioned for the case of the PSF library, we suggest for the correlation library to be normalized to one photon illuminating the JWST primary and that scaling to a given source magnitude be done as a function of the astrophysical properties of the occulted source (in this sense the correlation matrix is almost a correlation matrix).

Based on the ETC inputs then correlation matrix chosen to estimate the speckle noise for a given ETC calculation follows the decision tree on Figure 8-2:

A. Choice of the instrument and coronagraph setup.
B. Choice of the astrophysical scene (for the bright source and the reference images).
C. Choice of the coronagraphic observation strategy: based on the coronagraphic observation sequence (support for the “standard sequence as define by Soummer et al. is a “must have”).
D. Based on B and C find a in a lookup table the range of telescope/instrument states that correspond to the observing scenario.

Check with the JWST SOCCER Database at: https://soccer.stsci.edu
To verify that this is the current version.
E. Choice of a speckle calibration strategy: the ETC presents to the user the choice between available strategies (single and mean/median PSF subtractions are a “must have”).
F. Choice of the adequate correlation matrix based on D and E.

8.3 Internal interfaces/bookkeeping
When compared to other observing modes, coronagraphy requires ETC to identify and bookkeep three types of astrophysical sources:
1. The occulted source: entered manually by the user.
2. The reference source(s): entered manually by the user.
3. The off-axis source: most likely entered manually by the user.

This bookkeeping will then fold into both the correlation matrix library and the various calculations associated with the user needs discussed above. Because coronagraphy actually observes two astrophysical objects at the same time (the off-axis source is the main purpose of the science program and the bright source the main source of noise, hence the PSF subtraction) it is critical for the ETC to have the ability to identify internally this type of sources.

8.4 User interfaces
Except for this internal bookkeeping the CWG does not expect coronagraphy to have a major impact on the ETC interfaces except for:
- Giving the user the ability to clearly identify the type of sources as an input.
- Giving the user the ability to choose the PSF subtraction strategy.
- Providing the ability for the user to toggle between various sources of noise (photon, detector, background, speckle etc) in both the 1D and 2D representations resulting from the noise and SNR calculation. In the case of the 1D plots it is possible present the noise sources in a stacked plot. The 2D representation can be implemented by providind an image slider, where each individual noise source would be saved in a single plane and the combined noise would be another plane. The user could then see each of the noise sources separately, as well as seeing the combined effect.

This last bullet is actually of critical importance for coronagraphs users. Indeed when planning a coronagraph observation, the SNR on the off-axis source is strongly impacted by not only on exposure time but also on method for reference observations, PSF subtraction methods, background subtraction methods. It is not the vocation of the ETC to thoroughly guide the observers through the choices for the latter three “knobs”: the envisioned simulation module of the coronagraph pipeline will be used for that purpose. However the ETC ought to be able to help the observer to identify the dominant sources of noise and choose exposure time accordingly. In other words “expert coronagraph observations” feature too many parameters to optimize for the ETC to realistically capture all of them. However the CWG recommends for the ETC to support simulation of a few representative data acquisition and reduction methods, corresponding to “nominal use cases”.

Check with the JWST SOCCER Database at: https://soccer.stsci.edu
To verify that this is the current version.
The CWG believes that the ability for the user to toggle between various sources of noise in both the 1D and 2D representations resulting from the noise and SNR calculation will result in such an identification of the dominant sources of noise.
9 Conclusion

In this document we summarized the needs of an observer planning JWST coronagraph observations from an ETC standpoint. We have identified five high level needs, which in turn translate into a series of lower level “musts” and “wants” encompassing the ensemble of use cases currently envisioned by the Coronagraphs Working Group. Using the example of MIRI we carried out preliminary calculations of speckle noise of speckle noise Signal to Noise Ratio that illustrate the desired diagnostics associated with this source of noise that is specific to coronagraph. These calculations also demonstrate that the approach underlying the ETC engine is consistent with noise calculations methods currently used in the high-contrast imaging community. Note that the present document does not fully address all the specificities of coronagraph observations of off-axis extended sources: the particularities of this use case ought to be addressed in the future. Finally we identified interfaces that are specific to coronagraph: namely the use of a PSF and correlation libraries (and the associated bookkeeping). These concepts are common to the entire suite of observation planning and support tool associated with coronagraphy, and their structure will be the focus of a subsequent document.
## Appendix A. Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4QPM</td>
<td>Four Quadrant Phase Mask.</td>
</tr>
<tr>
<td>APT</td>
<td>Astronomer’s Proposal Tool</td>
</tr>
<tr>
<td>ETC</td>
<td>Exposure Time Calculator</td>
</tr>
<tr>
<td>FPM</td>
<td>Focal plane Mask</td>
</tr>
<tr>
<td>FSM</td>
<td>Fast Steering Mirror</td>
</tr>
<tr>
<td>JWST CWG</td>
<td>JWST Coronagraphs Working Group.</td>
</tr>
<tr>
<td>PSF</td>
<td>Point Spread Function</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
</tbody>
</table>
Appendix B. How to Generate Correlation Matrices

The calculation of the noise terms associated with speckles heavily relies on using a correlation matrix. In this appendix we describe how to generate such correlation matrices, we discuss how this method to quantify speckle noise compares with other approaches that have been published in the coronagraphic literature over the past decade.

B.1 Correlation matrix

Correlation matrices are the building block of the envisioned ETC noise calculation. As shown on Figure B-1, calculating them assumes that several realizations of the speckle noise that are representative of the observing conditions are available. The correlation matrix is then calculated by computing the pixel-to-pixel correlation, marginalizing of the representative range of telescope/instrument states. This approach is different from what is routinely done by coronagraphic observers as they usually seek to quantify detection limits based on only one single realization of the coronagraph exposure (very often co-added frames from PSF subtracted observing sequence). In this case coronagraph users assume ergodicity for the underlying random variable and derive one-dimensional detection limits based on the spatial statistical properties (mean and variance over a series of concentric annuli) of that image.

Because of our choice for the correlation matrix calculation illustrated on Figure A-1 requires several realizations of the PSF we ought to resort to simulations to generate the required ensemble of PSFs. Note however that the relevant ranges of telescope/instrument states underlying these simulations will be updated based on commissioning activities. Moreover this choice of noise calculation strategy will allow the observer to obtain two dimensional detection limits, which are not available when deriving speckle statistics based on a single image. The architecture suggested in this report also separates the PSF library and the correlation matrix library: this deliberate choice was made in order to provide the flexibility to separately quantify the computational and memory resources required in order to carry out the necessary calculations. The full trade-off associated with these choices are not the purpose of this report and ought to be studied in a separate communication.
Figure B-1 Synoptic of speckles SNR calculation.
Top left: range of telescope states corresponding to the observing sequence. Bottom left: range of PSFs obtained by propagating those OTEs through a MIRI PQPM+F1140C coronagraphic simulator. The pixel to pixel correlation matrix is built by marginalizing over the range of telescope states. Right: this correlation matrix is then used in conjunction with the coefficients associated with the signal extraction strategy to quantify the source SNR. This figure illustrates the case of raw speckles. For PSF subtraction the reference PSF is subtracted from the science PSF before calculation of the correlation matrix.

B.2 Comparison with other methods
Here we report on the result of our detailed numerical study to assess the accuracy of this noise calculation method with respect to “single images” approaches currently used in the literature. To do so we used the MIRI coronagraph simulator developed in the framework of Lajoie et al., generate an ensemble of PSFs that share the same OTE but various realizations of the Target Acquisition within a standard deviation of 5 mas. We then calculate the SNR=1 point source detection limit using the following five algorithms:

1. Mean over a series of concentric annulus. This corresponds to the “raw contrast” quantity in Lajoie. This method is mostly limited by the fact that the actual quantity driving the detection limit is the variance over the speckles. It also carries out statistics in over pixels instead of over units of angular resolution.
2. Variance over a series of concentric annulus. This method is mostly limited by the fact of carrying out statistics over pixels instead of over units of angular resolution.
3. **Mean over a series of concentric annuli of a matched filtered PSF** (using a template off-axis PSF). While the statistics are now carried out over true elements of angular resolution this method is mostly limited by the fact that the actual true quantity driving the detection limit is the variance over the speckles.

4. **Variance over a series of concentric annuli of a matched filtered PSF** (using a template off-axis PSF). In theory this quantity should yield detection limits that match the “eye test” on Figure 5-1. While this is true at large separations we observe a slight difference at small angular separation (below 1’’). This is due to poor speckle statistics at small separations, a caveat that has only been recently identified in the high-contrast imaging community (Mawet et al.) and can only be circumvent by using advanced statistical treatment of the problem (student-t distributions).

5. **ETC method**, which circumvent this latter problem since the “speckle sample” at small separations is increased by usage of multiple realizations of the coronagraph images.

Figure B-2 shows the comparison between these five methods in the case of the raw speckles. There we indicated in red and blue the sources at 1’’ and 2.8’’ that can be seen on Figure 5-1. This further illustrates the discussions above and demonstrates the robustness of the suggested ETC methods using an ensemble of PSFs and building correlation matrices accordingly. Figure A-2 shows the comparison between these five methods in the case of the single reference subtraction: as one would expect intuitively, when the noise has been “gaussinaized” by the PSF subtraction, Lafreniere et al., we observe better agreement between the various methods.

![Figure B-2 Comparison of the five approaches to quantify coronagraph detection limits in the case of raw speckles.](image)

We consider the case of a single PSF subtraction where all MIRI FQPM+F1140C target acquisition has been randomly drawn within a uniform distribution of standard deviation 5 mas. Putting these in perspective with Figure 5-1 (for which the brightness of the synthetic point sources was chosen to appears at SNR ~1) shows that the ETC method is a robust SNR estimator.
Figure B-3 Comparison of the five approaches to quantify coronagraph detection limits when using a reference PSF.

We consider the case of a single PSF subtraction where all MIRI FQPM+F1140C target acquisition has been randomly drawn within a uniform distribution of standard deviation 5 mas. Putting these in perspective with Figure 5-1 (for which the brightness of the synthetic point sources was chosen to appear at SNR ~1) shows that the ETC method is a robust SNR estimator. When compared to the case of raw contrast there is a better agreement between the various methods since the underlying noise statistics are close to a Gaussian distribution after PSF subtraction.

B.3 Table of features

In the table below we summarize the features of the ETC for coronagraphy that are described in this document. As part of a prioritization effort that occurred in Aug-Sept 2014 these features were categorized as follows:

- Basic use (B): this feature is absolutely necessary in order to do an ETC calculation and satisfy the Level 4 requirements.
- Basic to the workflow (BW): this feature is required in order to make use of the exploration and comparison features of the UI: things that help scientists to make science judgments during proposal planning.
- Integrated PPS experience (I): this feature supports the user's ability to use all the PPS tools in a coordinated fashion. (Clearly the MSA-ETC interaction falls in this category.) Items in this category should be ranked.
- User prioritization (P): (we believe) this feature is important to users. This may be for convenience, or to allow accurate modeling of the objects they want to observe.

Features in the latter three categories were the prioritized after discussions between SSB and the CWG.
## Table B-1 Summary and prioritization of the ETC features

<table>
<thead>
<tr>
<th>Cat</th>
<th>Rank</th>
<th>Feature</th>
<th>Output Type</th>
<th>High level User Need</th>
<th>Lower level User Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td>Estimated SNR for the off-axis astrophysical source (for all speckle noise configurations), display</td>
<td>Scalar</td>
<td>Multiple</td>
<td>Multiple</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>“Speckle free” exposure time to reach target SNR</td>
<td>Scalar</td>
<td>Standard imaging ETC</td>
<td>Speckle free exposure time to reach a given SNR for the off-axis source</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Saturation radius of the reference PSF for a given up the ramp time*</td>
<td>Scalar</td>
<td>Detector and coronagraph geometry</td>
<td>Saturation radius for a given up the ramp time</td>
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<tr>
<td>B</td>
<td></td>
<td>“Speckle free” SNR</td>
<td>Scalar</td>
<td>Standard imaging ETC</td>
<td>Speckle free off-axis source SNR given an exposure time</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Warning if the PSF is saturated at the location of the off-axis source.</td>
<td>Warning</td>
<td>Detector and coronagraph geometry</td>
<td></td>
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<tr>
<td>BW</td>
<td>1</td>
<td>1D display of error budget display of all sources of noise (ability to show multiple 1D plots)</td>
<td>1D Image</td>
<td>Error budget display of all sources of noise</td>
<td>Error budget display of all sources of noise</td>
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<tr>
<td>BW</td>
<td>2</td>
<td>1D detection limit, contrast, display</td>
<td>1D Image</td>
<td>Speckle noise in raw coronagraph data (worse case).</td>
<td>Speckle noise, Signal to Noise ratio.</td>
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<td>BW</td>
<td>7</td>
<td>2D detection limit contrast, display</td>
<td>2D Image</td>
<td>Multiple</td>
<td>Multiple</td>
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<tr>
<td>BW</td>
<td>16</td>
<td>Largest separation (in arcsec) at which the PSF will saturate</td>
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<td>Detector and coronagraph geometry</td>
<td>Largest separation for given up the ramp time</td>
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<tr>
<td>BW</td>
<td>18</td>
<td>Maximum allowable up the ramp time to avoid saturation of the reference PSF at a certain radius*</td>
<td>Scalar</td>
<td>Detector and coronagraph geometry</td>
<td>Exposure time for an azimuthally symmetric saturation zone</td>
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<tr>
<td>BW</td>
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<td>Warning if the off-axis source is located at saturated pixels.</td>
<td>Warning</td>
<td>Detector and coronagraph geometry</td>
<td>Warning if the off-axis source is located at saturated pixels.</td>
</tr>
<tr>
<td>I</td>
<td>3</td>
<td>2D PSF with asymmetric PSF structures clearly indicated, overlaid with the location of the off-axis source in the focal plane array for the chosen roll angle, display</td>
<td>2D Image</td>
<td>Detector and coronagraph geometry</td>
<td>Range of roll angles, preventing off-axis source/PSF structures overlap.</td>
</tr>
<tr>
<td>I</td>
<td>5</td>
<td>List of roll angles for which the off-axis source is not behind under the coronagraphic PSF structures, display</td>
<td>List of Scalars</td>
<td>Detector and coronagraph geometry</td>
<td>Range of roll angles, preventing off-axis source/PSF structures overlap.</td>
</tr>
<tr>
<td>Cat</td>
<td>Rank</td>
<td>Feature</td>
<td>Output Type</td>
<td>High level User Need</td>
<td>Lower level User Need</td>
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</tr>
<tr>
<td>P</td>
<td>1</td>
<td>2D display, of error budget display of all sources of noise</td>
<td>2D Image</td>
<td>Error budget display of all sources of noise</td>
<td>Error budget display of all sources of noise</td>
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<td>2</td>
<td>1D detection limit, (F_\text{lambda}), display</td>
<td>1D Image</td>
<td>Speckle noise, Multiple</td>
<td>Speckle noise, Multiple</td>
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<tr>
<td>P</td>
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<td>1D detection limit, apparent magnitude, display</td>
<td>1D Image</td>
<td>Speckle noise, Multiple</td>
<td>Speckle noise, Multiple</td>
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<td>P</td>
<td>6</td>
<td>2D detection limit, (F_\text{lambda}), display</td>
<td>2D Image</td>
<td>Speckle noise, Multiple</td>
<td>Speckle noise, Multiple</td>
</tr>
<tr>
<td>P</td>
<td>8</td>
<td>2D detection limit, apparent magnitude, display</td>
<td>2D Image</td>
<td>Speckle noise, Multiple</td>
<td>Speckle noise, Multiple</td>
</tr>
<tr>
<td>P</td>
<td>11</td>
<td>2D image with pixels shown as on/off depending on on saturation, overlaid with location of off-axis source</td>
<td>2D image</td>
<td>Detector and coronagraph geometry</td>
<td>Saturation radius for a given up the ramp time</td>
</tr>
<tr>
<td>P</td>
<td>12</td>
<td>Largest separation (in arcsec) at which the PSF will saturate “in the core”</td>
<td>Scalar</td>
<td>Detector and coronagraph geometry</td>
<td>Saturation radius for a given up the ramp time</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Strategy: apphot, raw</td>
<td>Algorithm</td>
<td></td>
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<tr>
<td>B</td>
<td></td>
<td>Strategy: apphot, realistic PSF subtraction</td>
<td>Algorithm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Strategy: apphot, optimal PSF subtraction</td>
<td>Algorithm</td>
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</table>

Check with the JWST SOCCER Database at: [https://soccer.stsci.edu](https://soccer.stsci.edu)  
To verify that this is the current version.