# Calibrating detector backgrounds for the Roman Coronagraph EXCAM detector

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## 1 Introduction

Accurate knowledge of detector background patterns in the absence of illumination is necessary for obtaining the correct zero-point of the science frames. The most important additive systematic offsets for the CGI EMCCD in EXCAM are fixed pattern noise (FPN), dark current, and clock-induced charge (CIC). All the frames needed for detector background calibration are obtained with the CFAM dark slide in place so that no light reaches EXCAM.

FPN comes into the signal data stream at the readout amplifier and is caused by electrical noise due to electromagnetic induction (EMI) at the CCD sense node. It is the last step prior to the digitization of the signal. As such FPN does not depend on the exposure time or the EM gain; it does depend on the camera proximity electronics (Prox-E) temperature, though. FPN has both a fixed repeatable component and a smaller time-variable component. The time-variable component effectively increases the read noise. Dark current is produced by thermally excited electrons and increases with sensor temperature, exposure time, and EM gain. CIC is produced from ionization as charge is transferred between pixels as the pixel charges are clocked. It increases with increasing EM gain and does not depend on exposure time.

Table 1: Summary of the characteristics of the three detector backgrounds

| | *Level varies unpredictably with time* | *Varies from pixel-to-pixel* | *Grows linearly with exposure time* | *Changes with EM gain* | *Present in prescan* |
|---|---|---|---|---|---|
| ***FPN*** | N/Y | Y | N | N | Y |
| ***Dark current*** | N | Y | Y | Y | N |
| ***CIC*** | N | Y | N | Y | Y |

Prior to TVAC, the expected rate for dark current and CIC were about 8 x $10^{-4}$ e-/px/s and 1 x $10^{-2}$ e-/px/fr, respectively (Nathan Bush, priv. comm.). FPN was expected to be much larger, though its value was not known.

## 2 TVAC calibrations

A strategy was developed for data collection during TVAC that leveraged the characteristics of each type of detector background shown in Table 1 as well as its magnitude. Specifically, FPN is the only significant detector background in short exposure, low-EM gain frames. CIC would dominate in short exposure, high-EM gain frames once FPN is subtracted, and dark current would dominate in long exposure, high-EM gain frames once FPN is subtracted.

From a photon transfer curve (PTC) analysis (using illuminated pupil images in TVAC), the DN to e- conversion factor (k-gain) and inherent read noise were determined to be 8.7 e-/DN and 130 e-, respectively. Given the magnitude of the read noise, measurement of CIC and dark current requires obtaining frames at high EM gain. For example, the effective read noise at EM gain of x7000 would be 130 e-/7000 = 0.02 e-/px. This is within a factor of two of the CIC noise in a frame and the dark current in a 100-second exposure frame. Table 2 gives the conditions under which each background dominates.

Table 2: Summary of conditions in which each detector background dominates

| | *Low EM gain* | *High EM gain* |
|---|---|---|
| *Short exposure* | FPN | FPN+CIC |
| *Long exposure* | FPN | FPN+Dark+CIC |

## 2.1 FPN

The FPN map was created from 98 zero exposure frames with EM gain set to unity. The frames were prescan bias corrected, cropped and then averaged to form a 1024 x 1024 array. The average pixel value was subtracted from the array, and then it was multiplied by the k-gain (8.7 e-/DN) to convert the units to e-/px/fr. Shown in Figure 1is a portion of the final FPN map. The FPN values range from about -250 e- to +250 e-.

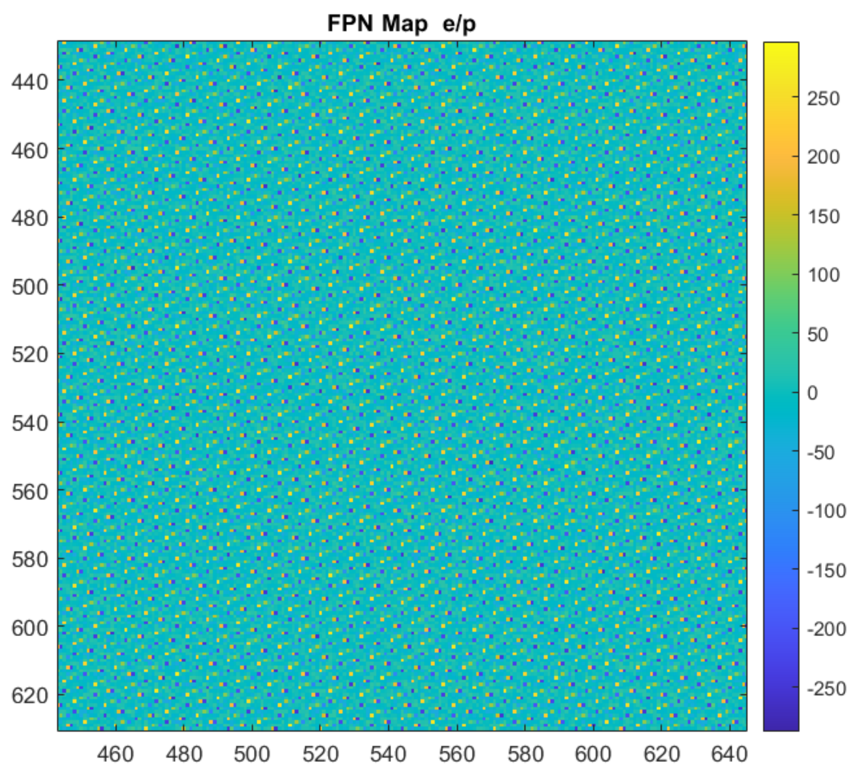


Figure 1: Central 200 x 200 pixel region of the FPN map image region (1024 x 1024 pixels) made from zero exposure unity gain frames taken during TVAC.

Figure 1:

From analysis of a separate set of 1-second exposure unity gain frames, the time-variable component of FPN was determined to be 19 e-/px/fr, much smaller than the inherent read noise.

## 2.2 CIC

The CIC map was made from 80 1-second frames with an actual EM gain of about x7815. Each frame was processed by correcting for prescan bias, multiplying by k-gain, and subtracting the FPN map. One frame with a cosmic ray hit was excluded from the analysis. The processed frames were then summed. As shown in Figure 2, the read noise dominates the "signal". It is clear that the standard "analog processing" approach will not suffice for creating the CIC map.

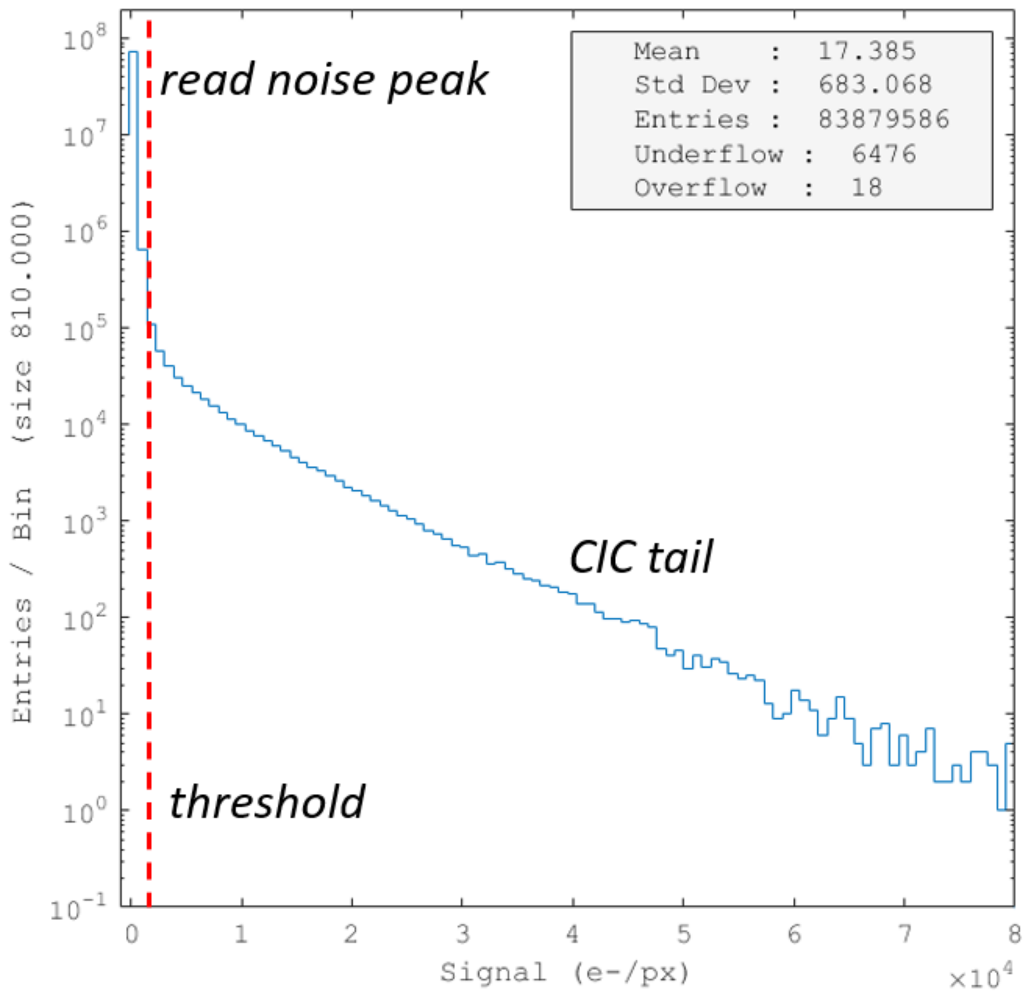


Figure 2: Histogram of pixel values in image region of FPN-corrected, co-added, short exposure, high-EM gain frames. The vertical dashed line shows the calculated threshold value.

In order to estimate the weak CIC signal, it is necessary to apply photon counting to the frames. The threshold factor, $\tau$, is set such that true N=1 (non-partial) events have 90% efficiency, $\varepsilon$:

$$\tau = -G\ln(\epsilon)/RN$$

where $G$ is the EM gain and $RN$ is the read noise. With $G$ = x7815 and $RN$ = 130 e-, $\tau$ is 6.3. The threshold is then $\tau \cdot RN$ = 820 e-. Photon counting was then applied to each pixel of each frame by setting the pixels with values > threshold to 1 and 0 otherwise. The signal for each pixel was then summed over all the frames. A photometric correction was then applied to each pixel value, $N_{br}$:

$$\lambda = -\ln\left[1 - \frac{N_{br}/N_{fr}}{e^{-\tau\, RN/G}}\right]$$

where $N_{fr}$ is the number of frames, and $\lambda$ is the mean expected value. This correction gives a result accurate to about 1 percent (Nemati 2020). The final delivered CIC map was made by smoothing the pixel values with a "moving mean" box with sides of 8 pixels. The mean value was 8.8 x $10^{-3}$ e-/px/fr.

The final map displays a noticeable pattern (Figure 3), which peaks at the lower right. There is also a column with slightly higher CIC than the average. The central region, where the dark hole will be projected, appears relatively uniform.

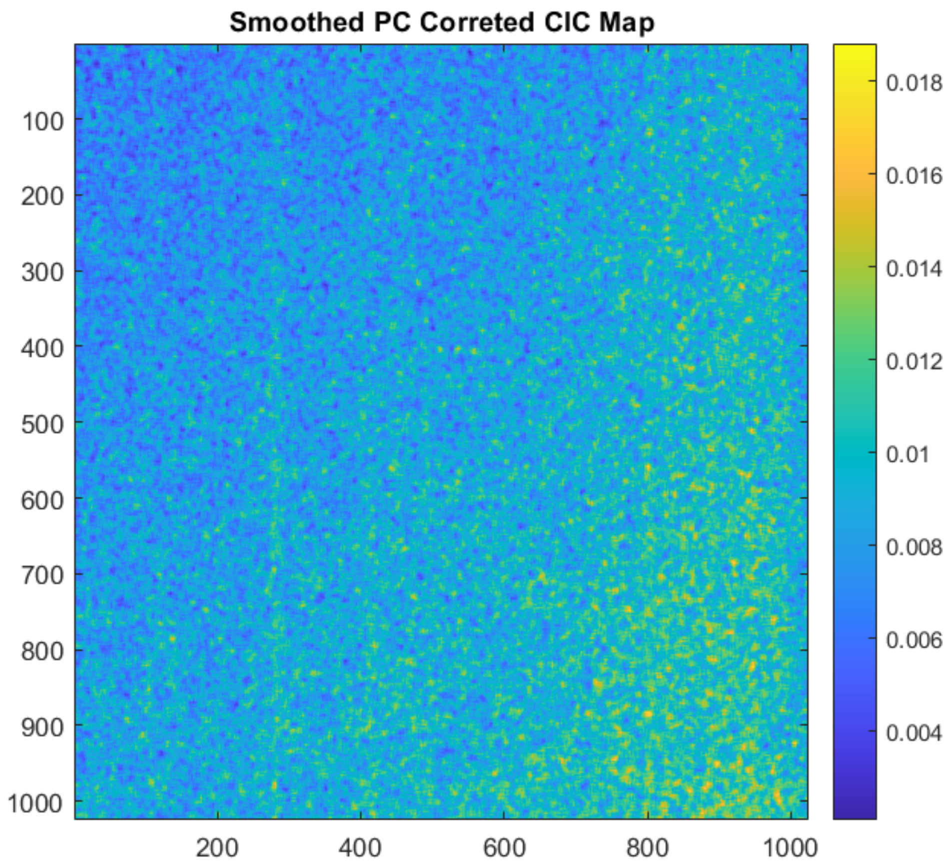


Figure 3: The final delivered TVAC CIC map. The units are e-/px/fr.

## 2.3 Dark current

The dark current map was made from 48 100-second frames with an actual EM gain of x7815 (the same value as the CIC frames). Figure 4 shows a sample unprocessed dark frame. Frames were prescan bias corrected, and the FPN and CIC maps prepared in the prior steps were applied.

Since the exposure times are long duration, each frame has about 2 or 3 cosmic ray hits. Cosmic ray hits were identified in a semi-automated way. Pixels affected by cosmic rays were masked with NaNs manually. A mean image was then calculated by using a mean function that excludes the NaN values.

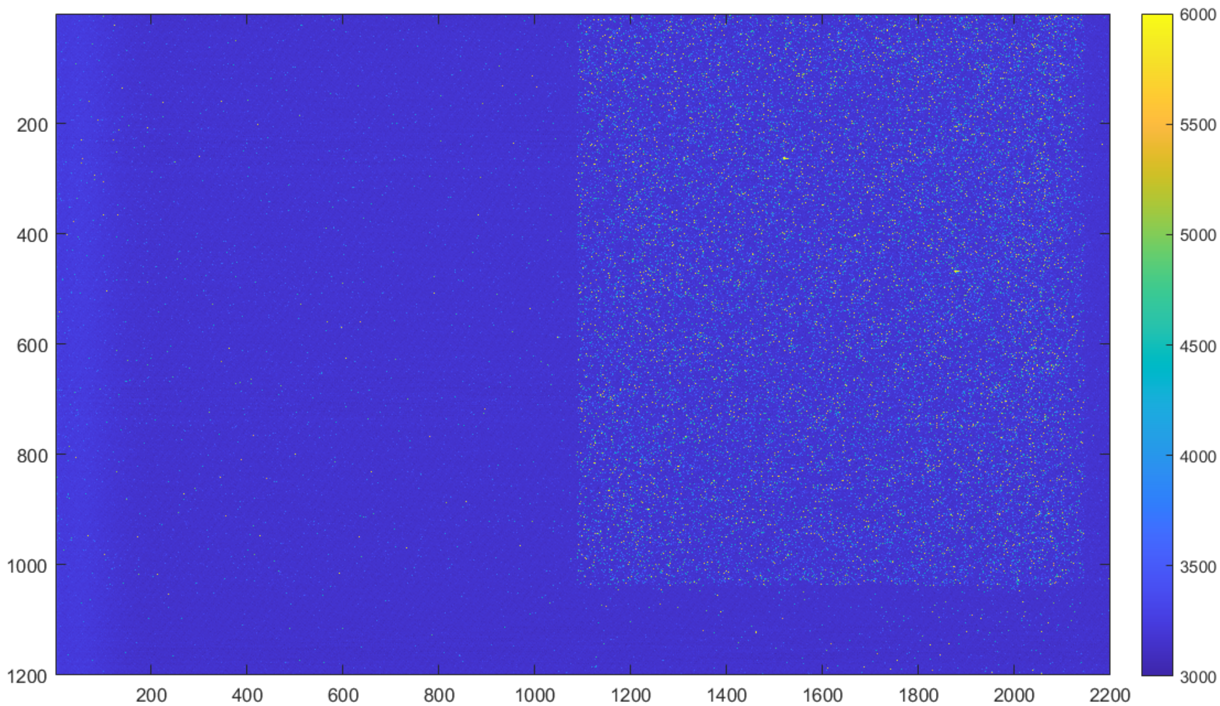


Figure 4: Unprocessed L1 dark frame with 100-second exposure time taken with EM gain of about x7815. Two cosmic ray hits are visible to the right of center (in the image region). CIC events are visible in the prescan region.

The histogram of the mean dark array is shown in Figure 5. Less than 1 percent of the pixels have negative values, indicating that the bias correction was slightly off. As with the CIC map, the pixel values were smoothed with a moving mean box 8 pixels on a side. This also has the effect of eliminating the negative pixel values. The final delivered map is shown in Figure 6. The highest dark current is at the upper right corner, near the readout amplifier. The mean dark current is 1.0 x $10^{-3}$ e-/px/s (3.6 e-/px/hr). The central region, where the dark hole will be projected, appears relatively uniform and is flanked on the left and right by higher dark current.

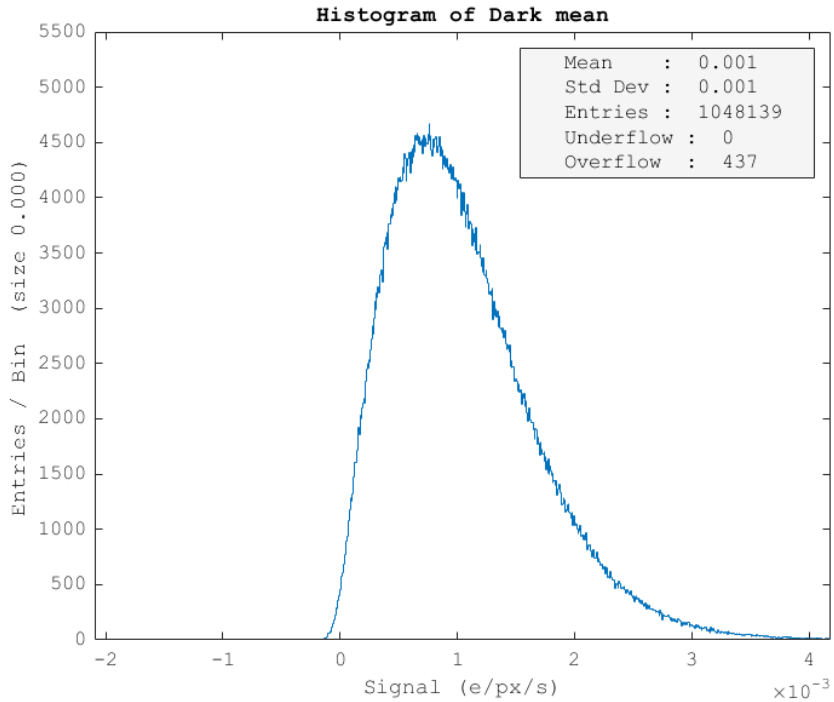


Figure 5: Histogram of the mean dark array. 0.34 percent of the pixels have negative values.

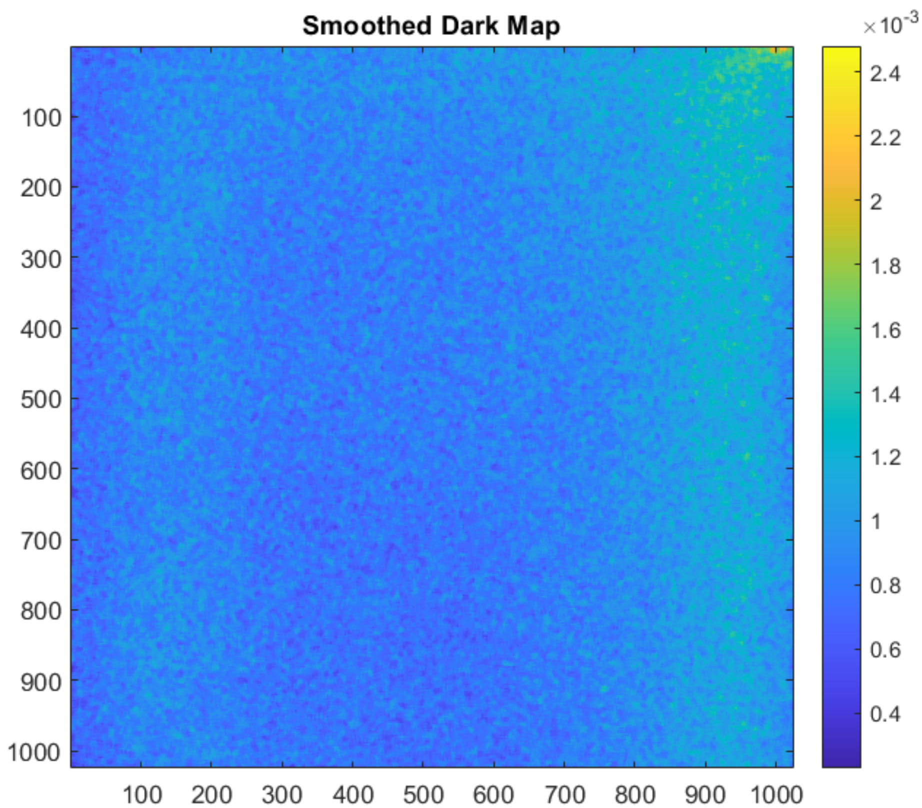


Figure 6: Final delivered TVAC dark map in units of e-/px/s.

# 3 Calibrating the science frames

Once all three detector background maps are made, they are then used to construct a 'master dark' array,

$$M = \frac{F + G \cdot t \cdot D + G \cdot C}{G} = \frac{F}{G} + t \cdot D + C \quad [e^{-}/px]$$

where *F*, *D*, and *C* are the FPN, dark current, and CIC maps, respectively. This master dark is applicable to a science frame of exposure time, *t* (sec), and EM gain, *G*.

The L2a → L2b processing pipeline calls for multiplying the science frame by k-gain, dividing by EM gain and then subtracting *M*.

# 4 Commissioning approach

Frame collection and preparation of detector background maps during commissioning (TTR5) and beyond will differ in several respects from the approach outlined above for TVAC. The primary difference is the ground processing software, which will solve for all three maps simultaneously using least-squares rather than produce each map separately. The software flags cosmic rays automatically and takes the flags into account when calculating means. In addition, it calculates a 'bias offset' from residual FPN+CIC in the prescan area; this accounts for any mismatch between the prescan and image areas (something that was not done in the analysis of TVAC data). Lastly, no smoothing is performed on the final maps (unlike the processing of the TVAC data); the software processes each pixel independently.

This new analysis method requires a minimum of a 2x2 combination of exposure time and EM gain frame sets. In addition, the current version of the code requires each combination to have the same number of frames. In the TVAC analysis three frame sets sufficed to calculate the maps (short exposure, low EM gain; short exposure, high EM gain; long exposure, high EM gain). However, in selecting the combinations of exposure time and EM gain to be used in commissioning, the same basic fundamentals employed during TVAC will be used. The following combinations of exposure time and EM gain are proposed for the baseline data collection (Table 3):

Table 3: Summary of number of frames to collect during commissioning (baseline)

| *# frames, total time (min)* | *EM gain = x1* | *EM gain = x1000* | *EM gain = x8000* |
|---|---|---|---|
| *t = 0 s* | 98, 4.9 | -- | 98, 4.9 |
| *t = 10 s* | -- | 98, 16.3 | -- |
| *t = 100 s* | -- | -- | 98, 163.3 |

The total exposure time is 3.2 hours. The total time spent on the longest exposure time frames is about twice as long as was spent during TVAC. This longer time spent collecting the 100 s frames is meant to compensate for the greater rate of cosmic ray hits in orbit.

There is also the option of acquiring a larger number of frames for extended performance, beyond the basic requirements for TTR5. Table 4 gives the required frames for such a case. It also assumes the analysis software has been upgraded to handle different numbers of frames for each combination.

Table 4: Summary of number of frames to collect for extended performance

| *# frames, total time (min)* | *EM gain = x1* | *EM gain = x1000* | *EM gain = x8000* |
|---|---|---|---|
| *t = 0 s* | 196, 9.8 | -- | 24000, 1200 |
| *t = 10 s* | -- | 196, 32.7 | -- |
| *t = 100 s* | -- | -- | 720, 1200 |

The total exposure time is 40.7 hours. The expectation is that the frames for constructing detector background maps will be collected with CGI as secondary on Roman. This way, the dark frames collection does not count as time against CGI.

**References**

Bijan Nemati, "Photon counting and precision photometry for the Roman Space Telescope Coronagraph," Proc. SPIE 11443, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, 114435F (13 December 2020); https://doi.org/10.1117/12.2575983