

CHEOPS Exposure Time Calculator – Manual

1 At a glance

The CHEOPS Exposure Time Calculator (ETC) provides users with an estimation of the photometric precision reached over pre-defined time intervals (also referred to as *durations*), that is 1 min, 10 min, 30 min, 1 h, 3h, and 6 h. In addition, the user may specify a custom duration. The calculations are based on noise estimates according to the expected mission performance, which includes all the major instrumental and white noise sources, and optionally account for light curve interruptions and stellar granulation. The input parameters are:

- Gaia G -band magnitude;
- stellar effective temperature T_{eff} ;
- stellar spectral type;
- exposure time t_{exp} ;
- target coordinates (or the observing *efficiency*).

The G -band magnitude along with T_{eff} enable the tool to compute the stellar magnitude in the CHEOPS passband and finally the target flux. Alternatively, the user may directly input the target flux in electrons per seconds [$e^- s^{-1}$]. The stellar spectral type (if specified) allows the tool to compute the noise contribution due to stellar granulation to be added to the noise budget. The exposure time is the time during which photons are collected to record an image. The efficiency of the visit (i.e. the time fraction spent on target and not interrupted by either Earth occultations, Earth stray light events, or South Atlantic Anomaly (SAA) crossings) can either be estimated by the tool itself from the target coordinates¹, or specified manually by the user.

2 How to use the CHEOPS Exposure Time Calculator

The expected photometric precision is obtained in a user friendly way via a web interface available online². A screenshot is shown in Figure 1. The editable parameters are contained in two boxes: the top box, *Input parameters*, contains the target parameters, while the bottom box, *Additional Parameters*, allows the user to specify the efficiency of the visit, the flux of the target in the CHEOPS passband, and a custom time interval

¹Note that the observing efficiency given by the ETC should be considered as a rough estimation. The ETC does not replace the *Feasibility Checker*, whose installation and user instructions are available at <https://www.cosmos.esa.int/web/cheops-guest-observers-programme/scheduling-feasibility-checker>

²<https://cheops.unige.ch/pht2/exposure-time-calculator/>

Exposure Time Calculator

Help

Input Parameters

Target G Magnitude

Target Effective Temperature [K]

Spectral type (stellar granulation)

Exposure Time [s]

Right Ascension [hh:mm:ss / decimal deg]

Declination [dd:mm:ss / decimal deg]

Additional Parameters

Specify observation duration

Defined time interval [h]

Specify flux in CHEOPS passband

Flux [e-/s]

Specify visit/observation efficiency

Efficiency [%]

Calculate Clear

Calculation Results

Saturation level at PSF peak [% FWC]						
	1 MIN	10 MIN	30 MIN	1 H	3 H	6 H
ASSUMING 100% EFFICIENCY						
Stellar granulation noise	11.43	10.61	10.21	9.77	8.01	5.37
Photon noise	300.64	95.07	54.89	38.81	22.41	15.85
Total noise including stellar granulation	344.74	135.89	99.52	87.02	79.42	77.22
Total noise without stellar granulation	344.55	135.47	99	86.47	79.02	77.04
ASSUMING COMPUTED MAXIMUM EFFICIENCY						
Stellar granulation noise	11.43	10.61	10.21	9.77	8.01	5.37
Photon noise	300.64	122.74	67.23	47.54	27.44	19.41
Total noise including stellar granulation	357.05	160.56	110.76	92.85	81.33	78.21
Total noise without stellar granulation	356.87	160.21	110.29	92.33	80.94	78.03
ASSUMING COMPUTED MEDIAN EFFICIENCY						
Stellar granulation noise	11.43	10.61	10.21	9.77	8.01	5.37
Photon noise	300.64	134.45	72.92	50.82	29.2	20.6
Total noise including stellar granulation	361.77	171.13	115.52	95.63	82.08	78.59
Total noise without stellar granulation	361.59	170.8	115.06	95.13	81.69	78.4

Comment on exported PDF

Export results

Figure 1: The web interface of the CHEOPS ETC.

over which to compute the noise. The *Additional Parameters* are optional and only need to be set if the user wants or needs to specify them.

Once the input is set, the user triggers the computation by clicking on the `Calculate` button. The derived noise estimates with and without accounting for interruptions in the observation (no interruptions means 100% efficiency during the visit) and stellar granulation noise can be read off below. The outputs are described in detail in Sec. 2.4.

Via the button `Export Results`, the user creates a .pdf file containing the results of the computation. A user-defined comment to appear on the pdf can be specified in the field *Comment on exported PDF*.

2.1 Exposure times

At the bottom of the ETC website, the user can find guidelines to select appropriate exposure times for the individual photometric exposures. The exposure time value t_{exp} must lie in the range between 0.001 s and 60 s. The exposure time can never exceed 60 seconds (hard limit), independently of the magnitude of the star.

The CHEOPS CCD has a very good linear behaviour with respect to the incoming photons. Linearity is almost perfect inside the “linear regime”, which holds when

the number of generated charges fill between 10% and 70% of the full well capacity (FWC = $114\,000\ e^- s^{-1}$). Although departures from linearity outside the linear regime are well characterised and can be corrected for³, it is recommended that pixels inside the target’s PSF fall within the linear regime, when possible.

The user should always verify that the percentage of the FWC of a pixel filled by the highest peak of the PSF⁴ is below 100%. More strictly, the suggested maximum exposure time is the one where the PSF peak fills 85% of the FWC to provide enough margin to clearly avoid pixel saturation (for computing the saturation level at the PSF peak see Sec. 3.4). In case of saturation, the charge is not conserved, therefore it is strongly recommended that the exposure time is never higher than the suggested maximum exposure time. On the other hand, the suggested minimum exposure time is the one corresponding to the PSF peak filling 10% of the FWC to minimise the number of pixels affected by large non-linearity corrections.

In short, it is strongly recommended to select t_{exp} close to the suggested maximum exposure time (or to set $t_{\text{exp}} = 60\text{ s}$ if the FWC-filling is lower than 85%), to keep the instrumental noise to a minimum. The user is responsible for selecting the correct exposure time and may have reasons not to follow the guidelines given above. For example, the user might be interested in shorter exposure times than recommended to have a faster cadence of images or imagettes. More details are available in the CHEOPS Observers Manual, see especially Table 2 and Sec. 2.1.4 to 2.1.7.

2.2 Input Parameters

- **Target G Magnitude:** the apparent magnitude of the target in the Gaia *G*-band.
- **Target Effective Temperature:** T_{eff} of the target star (in Kelvin) within the allowed range of 2300 to 40 000 K.
- **Spectral type (stellar granulation):** the spectral type of the target star is needed to compute the contribution of stellar granulation to the noise. The available spectral types of Main-Sequence stars from F0V to M9V are accessible from a drop-down menu and they are reported in Tab. 1.
- **Exposure Time:** The exposure time of the individual CHEOPS exposures (in seconds). See Section 2.1 for suggestions on exposure times.
- **Right Ascension:** The target right ascension (RA) in decimal degrees, or in sexagesimal format [hh:mm:ss]
- **Declination:** The target declination (DEC) in decimal degrees, or in sexagesimal format [dd:mm:ss]

Both the *G*-band magnitude and T_{eff} are needed to compute the target flux, unless the user wants to manually input the flux after enabling the optional field `Specify flux in CHEOPS passband`. Both RA and DEC are needed to compute the *efficiency* unless the user wants to manually enter it by enabling the optional field `Specify visit/observation efficiency`. See Sec. 2.3 for further details.

³The CHEOPS data reduction pipeline corrects for non-linearity

⁴The highest peak of the PSF (one pixel) contains 0.475% of the total flux. Please check the CHEOPS Observers Manual (Sec. 2.1.3) for more details: https://www.cosmos.esa.int/documents/1416855/2010860/CHEOPS-UGE-PSO-MAN-001_i1.01_Observers+Manual_A01_release.pdf/

2.3 Additional Parameters

- **Specify flux in CHEOPS passband.** Ticking this box allows the user to specify the target flux $F_{\text{CH}} [e^- \text{ s}^{-1}]$ in the CHEOPS passband. If not ticked, the ETC tool calculates F_{CH} from the G -band magnitude and T_{eff} as described in Section 3.4.
 - **Flux:** F_{CH} expressed in electrons per second. This value is only used if the box `Specify flux in CHEOPS passband` is ticked.
- **Specify visit/observation efficiency.** Due to Earth occultations, Earth stray light events and passages through the SAA, CHEOPS observations are typically interrupted for a fraction of the orbit. Ticking this box allows the user to specify the target observing efficiency (i.e. the fraction of time spent on-target). If the box is not ticked, the efficiency is taken from a pre-computed table based on the target coordinates (see Section 3.2.1). Note that the pre-computed table makes strong assumptions and have limited accuracy; it serves for orientation only and cannot replace proper estimation using the *Feasibility Checker*.
 - **Efficiency:** The user-specified observing efficiency expressed as percentage [%]. Efficiency refers to the fraction of the observation during which data are obtained, that is the time outside Earth occultations, Earth stray light events or passages through the SAA. This value is taken into account only if the box `Specify visit/observation efficiency` is ticked.
- **Defined time interval.** Besides the default time scales over which to compute the noise (i.e. 1 min, 10 min, 30 min, 1 h, 3 h, and 6 h), the user can specify an additional custom duration for the noise computation by ticking this box.
 - **Duration:** The user-specified duration expressed in hours [h].

2.4 Calculation Results

Results are organised in tabular form. The first line reports the **Saturation level at PSF peak [% FWC]**, computed according to Eq. (8) in Sec. 3.4. This line is then followed by two (or three) tables that summarize the noise estimates computed over default time intervals (i.e. 1 min, 10 min, 30 min, 1 h, 3 h, and 6 h) plus a further time interval specified by the user (optional). The first table reports the noise estimates when assuming 100% efficiency and it may be followed either by: (i) one further table reporting the noise estimates at the user-specified value of the efficiency; or (ii) two further tables reporting the noise estimates when assuming the maximum and median efficiency values as extracted by the tool following (RA, DEC) interpolation from the table of efficiencies described in Sec. 3.2.1. Option (i) applies when the user ticks the optional box `Specify visit/observation efficiency`, otherwise option (ii) holds. Keep in mind that computing the noise at 1 min duration makes sense only when the efficiency is equal to 100%.

Each table reports the following four rows:

- **Stellar granulation noise:** total stellar granulation noise (*flicker*) affecting the measurement (in ppm) computed as detailed in Sec. 3.3.
- **Photon noise:** photon noise affecting the measurement (in ppm).

- **Total noise including stellar granulation:** the total noise affecting the measurement including *flicker* (in ppm).
- **Total noise without stellar granulation:** the total noise affecting the measurement, but without the *flicker* contribution (in ppm).

2.5 Export to pdf

A pdf containing the details of the computation can be created via the button **Export results**. Optionally, the user can add a comment to the pdf file by filling in the *Comment on exported PDF* field.

2.6 To keep in mind

Some caveats for the preparation of an observation request (see CHEOPS Observers Manual for more details):

- The observer is free to select the exposure time that best suits her/his science case (it is strongly suggested to avoid pixel saturation though). However, due to the readout procedures in place, exposure time values $t_{\text{exp}} \approx 1$ s produce an image approximately every two seconds, while if $t_{\text{exp}} > 1.05$ s, an image is produced with a frequency equal to t_{exp}^{-1} . For bright stars for which a suitable t_{exp} should be close to 1 s, setting t_{exp} slightly greater than 1.05 s is recommended to maximise the duty cycle. Take this and the guidelines about t_{exp} (Sec. 2.1) into consideration to select the exposure time.
- Noise due to stellar background is not accounted for in the ETC and highly depends on each particular case. But, as a rule of thumb, avoid having close stellar companions (i.e. that overlap or almost overlap with the target's PSF), especially if they are brighter or roughly of the same brightness as your target.
- The cadence of the stacked images will be better than 1 stacked image every 60 seconds. The number of images (and in some cases also imaggettes) being stacked depends on the exposure time. Check the CHEOPS Observers Manual (Sect 2.1.7) to prepare the observation request in a smart way.

3 Assumptions and computation procedures

3.1 Main noise components

The noise sources used in this ETC are divided in *white* (σ_{white}), *systematic* (σ_{sys}), and *stellar* (σ_{star}) components (see Sec. 2.2 of the Observer's Manual).

The *white noise* components are photon noise (of the target and also of other sources like zodiacal light, stray light, hot pixels, self-smearing, dark current), readout noise, quantisation noise, and cosmic rays. These noise amplitudes are scaled to the duration of interest. White noise amplitudes are further adapted taking into account the limited observing efficiency when computing the appropriate output values.

The *instrumental systematic noise* components are stray light, flat field effects, variable dark current, analog electronic stability, timing errors, gain variability and quantum efficiency changes. With the exception of stray light, dark current variability and

flat-field effects, these noise components have constant amplitudes. The amplitude of the dark current variation is derived from the thermal stability of the instrument.

Additional *stellar noise* as expected from stellar granulation is derived for the timescale of interest as described in Section 3.3. Both granulation and instrumental systematic noise components are not affected by changes in the observing efficiency.

The combined noise value consists of the individual noise components added in quadrature. In detail, the photon noise is calculated via

$$\sigma_{phot} = \frac{1}{\sqrt{N_{phot}}}, \quad (1)$$

where N_{phot} is the number of photo-electrons registered by CHEOPS during the timescale of interest, and σ_{phot} is then added in quadrature to the other white noise components mentioned above to compute σ_{white} . The total noise (i.e. the uncertainty on the measured flux level) is calculated via

$$\sigma_{tot} = \sqrt{\sigma_{white}^2 + \sigma_{syst}^2 + \sigma_{star}^2} \quad (2)$$

for continuous observations (i.e. 100% efficiency), as well as for interrupted observations (i.e. efficiency lower than 100%) as detailed in Sec. 3.2. $\sigma_{star} = 0$ is assumed when calculating the output values that do not include the effect of granulation.

3.2 Observing efficiency

Gaps in the light curves exist due to Earth occultations, passages of the satellite through the SAA and periods during which the straylight exceeds observationally acceptable limits. The white noise components are adapted to account for this effect via

$$\sigma_{gap} = \sqrt{\frac{E}{100}} \sigma_{no\ gap}, \quad (3)$$

where $\sigma_{no\ gap}$ is the precision in the absence of gaps, while σ_{gap} is the precision for a reduced observing efficiency E (given in %).

3.2.1 Tabulated observing efficiency

Unless the `Specify visit/observation efficiency` option is activated and thus the efficiency is inputted by the user, the tool extracts both the maximum and the median efficiency values from a pre-computed table according to the target (RA, DEC). In detail, this table contains efficiencies at a given (RA, DEC) and on a daily grid for ‘standard’ visits defined as being 7 orbits (~ 11.5 hours) long and targeting a $G = 6$ magnitude star. Such standard visits aim at averaging the contributed interruptions from Earth occultations, Earth straylight events and SAA crossings. Please note that these values are to be understood as approximate and cannot replace a more thorough efficiency calculation using the *Feasibility Checker* tool.

3.3 Flicker

The amplitude of the stellar noise created by granulation (*flicker*) is calculated for the timescale of interest depending on the stellar spectral type. To do so, we use different high time-resolution simulated light curves (one for each spectral type listed in Tab. 1)

that include only variations induced by stellar granulation. An example light curve is shown in Figure 2 (left panel). We binned these light curves in different time intervals up to 9 hours, and measured the RMS for each binning choice. For each light curve we then fit the derived RMS values by a function of the form

$$\text{RMS} = c_1 + c_2 B + c_3^{c_4 B}, \quad (4)$$

where B is the bin size and c_i ($i = 1, 2, 3, 4$) are the best-fit coefficients retrieved for each light curve (i.e. for each spectral type). An example showing the trend of the flux RMS against B is shown in the right panel of Figure 2. The c_i coefficients are finally listed in a table (*flicker Table*) as a function of the stellar spectral type. The ETC tool automatically reads the *flicker Table* and collects the c_i coefficients corresponding to the spectral type of the target to then compute the amplitude of the flicker noise σ_{star} over the desired time scale duration following Eq. (4).

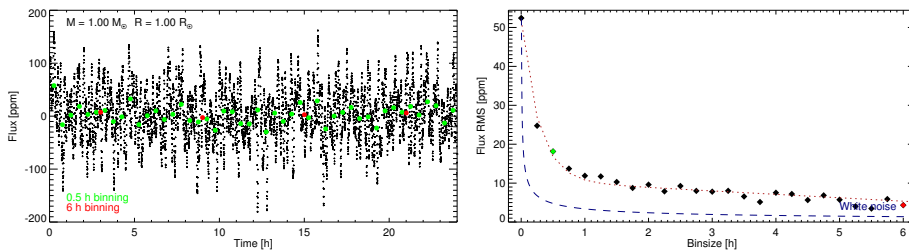


Figure 2: Flicker estimate from a simulated light curve. *Left panel*: a simulated flicker light curve unbinned (black), binned in 0.5 h (green) and 6 h (red) intervals. *Right panel*: The RMS of the binned light curve against the bin size together with the best-fit curve (dotted deep-red line); the white noise curve is displayed by the dashed blue line.

3.4 Star

For a given target, the number of photo-electrons per second measured by CHEOPS is computed depending on T_{eff} and the Gaia G -band magnitude.

First, the Vega photon flux F_0 incident on the telescope aperture is calculated as the integral of the Vega SED over the 330—1100 nm range (λ_{range}) multiplied by the CHEOPS collecting area (circular aperture with a radius of 30 cm), hence obtaining $F_0 = 3.6575 \cdot 10^9$ photons per second.

Then, the Vega photon flux in the CHEOPS- and Gaia G -passbands ($F_{0,\text{CH}}$ and $F_{0,G}$, respectively) is derived. In detail, $F_{0,\text{CH}}$ is computed by multiplying F_0 by the wavelength integral over λ_{range} of the product of the Vega SED, the optical throughput of the CHEOPS telescope⁵, and the quantum efficiency of the CHEOPS CCD; we obtained $F_{0,\text{CH}} = 1.8347 \cdot 10^9$ photons per second. Instead, $F_{0,G}$ is obtained after multiplying F_0 by the wavelength integral over λ_{range} of the product of the Vega SED and the Gaia G -passband.

Similarly, F_{CH} and F_G denote the photon flux of the target in the CHEOPS- and G -bandpass, respectively. However, they are computed using a black body (BB) spectrum at the effective temperature of the target ($T_{\text{eff,target}}$), rather than using the observed SED.

⁵The global throughput tables are available from the AO-1 website: <https://www.cosmos.esa.int/web/cheops-guest-observers-programme/ao-1>

Therefore, the conversion between the Gaia G magnitude and the CHEOPS magnitude (m_{CH}) is done using the following equation

$$\delta_{\text{CH-G}} = m_{\text{CH}} - G = -2.5 \log \left(\frac{F_{\text{CH}} \text{SF}(T_{\text{eff,target}})}{F_{0,\text{CH}}} \frac{F_{0,G}}{F_G \text{SF}(T_{\text{eff,Vega}})} \right), \quad (5)$$

where $\text{SF}(T_{\text{eff}})$ is the T_{eff} -dependent scale factor that has been empirically derived to account for the difference between the observed flux and the BB-based flux:

$$\text{SF} = -2.0074 \cdot 10^{-6} T_{\text{eff}} + 0.94604, \quad (6)$$

and $T_{\text{eff,Vega}} = 9600$ K.

The terms to convert G into m_{CH} as computed via Eq. (5) for a wide grid of T_{eff} values are reported in a table that the ETC tool interpolates according to $T_{\text{eff,target}}$; m_{CH} is then computed from G and $\delta_{\text{CH-G}}$. Once m_{CH} has been derived, the photon flux of the target in the CHEOPS passband is computed as

$$F_{\text{CH}} = F_{0,\text{CH}} \cdot 10^{-0.4m_{\text{CH}}} \quad (7)$$

The saturation level (SAT) at the PSF peak can be expressed as a percentage of the FWC via

$$\text{SAT} = \frac{\text{PSF}_{\text{hp}} F_{\text{CH}} t_{\text{exp}}}{\text{FWC}}, \quad (8)$$

where $\text{PSF}_{\text{hp}} = 0.475\%$.

Table 1: Spectral types for which the computation of stellar granulation has been implemented.

Spectral type
F0V
F1V
F2V
F3V
F4V
F5V
F6V
F7V
F8V
F9V
G0V
G1V
G2V
G3V
G4V
G5V
G6V
G7V
G8V
G9V
K0V
K1V
K2V
K3V
K4V
K5V
K6V
K7V
K8V
K9V
M0V
M1V
M1.5V
M2V
M2.5V
M3V
M4V
M4.5V
M5V
M5.5V
M6V
M7V
M7.5V
M8V
M9V