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 a user-specified time interval or duration. The calculations are based on noise estimates according to the expected mission performance, as well as all major instrumental noise sources, include photon noise, and optionally light curve interruptions and stellar granulation. The input parameters are the stellar spectral type, V-band magnitude, duration of interest, target coordinates (and/or observing efficiency) and exposure time. The efficiency, (i.e., the time fraction spent on target and not interrupted by Earth occultation and/or SAA crossing) of the visit can either be estimated by the tool itself from the target coordinates[1], or specified manually by the user. The stellar spectral type is selected from a list of main-sequence stars for which the flux that CHEOPS is expected to measure has been calculated. In case of targets with spectral types different from those available, the user may also specify directly the expected flux in the CHEOPS passband in electrons per second as an input.

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 online[2]. A screenshot is shown in Figure 1 . The editable parameters are contained in two boxes: the top box, *Input parameters*, contains the target parameters, and the bottom box, *Additional Parameters* allows to specify the efficiency of the visit (i.e. time spent on target and not interrupted by Earth occultation and/or SAA crossing) and/or the flux of the object in the CHEOPS passband (in case this is not covered by the *Stellar Type* input parameter). 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.

Then, the derived precision with and without accounting for interruptions in the observation (i.e. no interruptions are equivalent to 100% efficiency during the visit) and stellar granulation noise can be read off below. The outputs are described further in Section 2.5.

Via the button `Export Results`, the user can create 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".

[1] Note that the observing efficiency given by the ETC should be considered as a rough estimation. The ETC does not replace the feasibility checker.

[2] `https://cheops.unige.ch/pht2/exposure-time-calculator/`

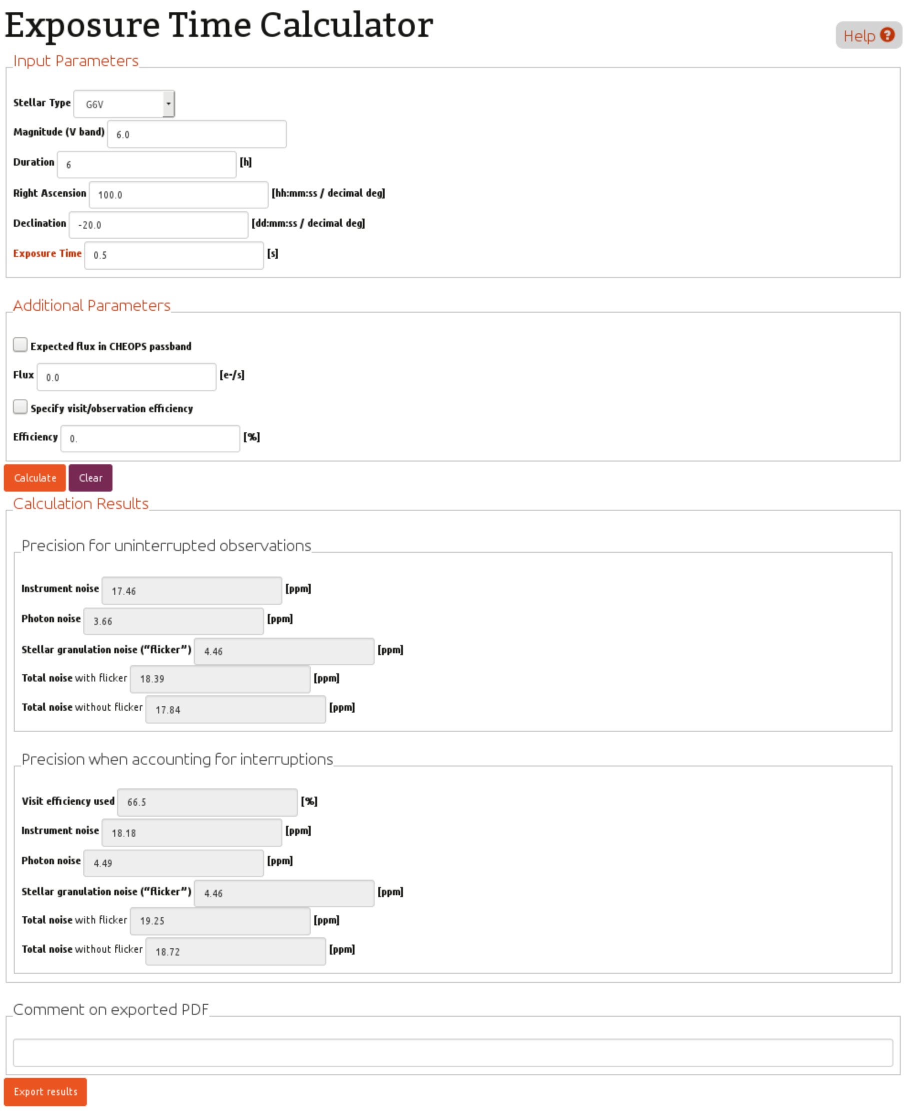

Figure 1: The web interface of the CHEOPS ETC.

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. These are in the form of tables listing a range of suggested exposure times for three example spectral types and magnitudes between V = 6 and V = 13.

The CHEOPS CCD has a very good linear behaviour with respect to the incoming photons. Linearity is almost perfect inside the "linear regime", i.e. when the number of charges generated fill between 10% and 70% of the full well capacity. Although departures from linearity outside the linear regime are well characterised and can be corrected[3], it is reccommended that pixels inside the target's PSF fall within the linear regime, when possible. Due to the steep gradients of the PSF, it can happen that several pixels inside the PSF are outside the linear regime. To minimise the number of pixels affected by large non-linearity corrections, it is recommended not to go below the suggested minimum exposure time (which corresponds to the time needed to fill 10% of the full well capacity at the highest peak of the PSF), nor above the suggested maximum exposure time (which corresponds to the time needed to fill 98% of the full well capacity at the highest peak of the PSF [4]). It is strongly recommended that the exposure time is never higher than the maximum suggested exposure time, which can result in the saturation of the pixel. In the case of saturation charge is not conserved.

The exposure time can never exceed 60 seconds (hard limit), independently of the magnitude of the star. More details are available in the CHEOPS Observers Manual, see especially Sec. 2.1.4 to 2.1.7.

2.2 Non-standard SEDs

In the case of targets other than stars with spectral types listed in Table 1, the user can use the option "Expected flux in CHEOPS passband" (as described in Section 2.4) and manually input the estimated flux that CHEOPS is expected to measure. To compute this value, users should assume a telescope diameter of 32 cm and use the global throughput tables available from AO-1 website[5].

2.3 Input Parameters

- **Stellar Type:** The spectral type of the target star. The values listed in Table 1 of this document are available from a drop-down menu.
- **Magnitude (V band):** The apparent V-band magnitude of the target star.
- **Duration:** The duration (in hours) for which the calculation should be performed.
- **Right Ascension:** The target right ascension in decimal degrees, or in hexagesimal format [hh:mm:ss]
- **Declination:** The target declination in decimal degrees, or in hexagesimal format [dd:mm:ss]
- **Exposure Time:** The exposure time of the individual CHEOPS exposures. See Section 2.1 for suggestions on exposure times.

2.4 Additional Parameters

- **Expected flux in CHEOPS passband:** Ticking this box allows to specify the flux in the CHEOPS passband. If not ticked, the flux will be calculated from tabulated values as described in Section 3.4.

[3] The CHEOPS data reduction pipeline corrects for non-linearity

[4] The highest peak of the PSF (one pixel) contains 2% of the total flux, according to the measurements done on ground. Please check the CHEOPS Observers Manual for more details (Sec. 2.1.3)

[5] `https://www.cosmos.esa.int/web/cheops-guest-observers-programme/ao-1`

- **Flux**: The target flux in the CHEOPS passband in electrons per second. This value is only used if the box *Specify CHEOPS flux* is ticked.

- **Specify visit/observation efficiency:** Due to Earth occultations and passages through the South Atlantic Anomaly, CHEOPS observations are typically interrupted for a fraction of the orbit. Ticking this box allows 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. Note that the pre-computed tables make strong assumptions and have limited accuracy (see Section 3.2.1). They serve for orientation only and cannot replace proper estimation using the *Feasibility Checker*[6].

- **Efficiency:** The user-specified observing efficiency in % . Efficiency refers to the fraction of the observation during which data will be obtained, i.e., the time outside Earth occultations or passages of the South Atlantic Anomaly. This value is taken into account only if the box *specify efficiency* is ticked.

2.5 Calculation Results

Precision for uninterrupted observations

- **Instrument noise:** Total instrumental noise affecting the measurement in parts-per-million (ppm). This contains the instrumental noise contributions as detailed in the CHEOPS Observers Manual, Sec. 2.2.

- **Photon noise:** Photon noise affecting the measurement in ppm.

- **Stellar granulation noise ("flicker"):** Total stellar granulation noise ("flicker") affecting the measurement in ppm. See section 3.3 for details of the flicker model that has been used in the tool.

- **Total noise with flicker:** The total noise affecting the measurement, assuming no interruptions and including stellar granulation ("flicker") noise.

- **Total noise without flicker:** The total noise affecting the measurement, assuming no interruptions but without stellar granulation ("flicker") noise.

Precision when accounting for interruptions

- **Visit efficiency used:** the efficiency used for deriving the values given below. Depending on whether the option "specify efficiency" was activated, this value is either the user-specified efficiency, or the value found from precomputed tables.

- **Instrument noise:** Total instrumental noise affecting the measurement in parts-per-million (ppm), assuming the efficiency given above. This contains the instrumental noise contributions as detailed in the CHEOPS Observers Manual, Sec. 2.2.

- **Photon noise:** Photon noise affecting the measurement in ppm, assuming the efficiency given above.

[6] installation and user instructions available from the AO-1 website `https://www.cosmos.esa.int/web/cheops-guest-observers-programme/ao-1`

- **Stellar granulation noise ("flicker"):** Total stellar granulation noise ("flicker") affecting the measurement in ppm. See section 3.3 for details of the flicker model that has been used in the tool.

- **Total noise with flicker:** The total noise affecting the measurement, assuming the efficiency given above and including stellar granulation ("flicker") noise.

- **Total noise without flicker:** The total noise affecting the measurement, assuming the efficiency given above and without stellar granulation ("flicker") noise.

2.6 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 this PDF via the "Comment on exported PDF" field. To support applications for observing time, this PDF output of the relevant computations will need to be uploaded to the *Phase I Proposal Handling Tool*.

2.7 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 (is it strongly suggested to avoid pixel's saturation though). However, due to the readout procedures in place, exposure times $\lesssim$1 second produce an image approximately every two seconds, while if the exposure time is set to 1.05 s, an image will be produced almost every second. Take this and the suggested exposure time range into consideration to select the exposure time.

- Noise due to stellar background is not accounted for in the ETC. This 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 brightnenss 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 imagettes) being stacked depends on the exposure time. Check the CHEOPS Observers Manual to prepare the observation request in a smart way (see Sect. 2.1.7).

3 Assumptions and computation procedures

3.1 Main noise components

The noise sources used in this ETC are divided in *white*, *systematic*, and *stellar* components (see Sect. 2.2 of the Observer's Manual).

The **white noise** components are target photon noise, sky background, readout noise on the target, readout noise on the sky, background dark current, quantization 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 **systematic instrumental noise** components are stray light, flat field effects, variable dark current, analog electronic stability, timing errors, gain variability and quantum efficiency changes. With exception of stray light, dark current variability and flat-field effects, they have constant amplitudes.

The **stray light** contribution is set to the allocated values of 5 ppm for ($6 \leq V \leq 9$) stars and 70 ppm for ($9 < V \leq 12$) stars. For stars brighter than V=6 or fainter than V=12, it is calculated based on scaling the expected flux contribution. This means that, all conditions being the same, there is a jump in the estimated noise at V=9. Keep in mind that this is due to the allocation made to the straylight contamination (and related to the science requirements). The allocation aims to put an upper limit to this noise source and it is in line with the way the feasibility checker works. Please look at the CHEOPS Observer Manual or at the Feasibility Checker guidelines for details.

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. With σ_i denoting the individual instrumental (white and systematic) noise components, the instrumental noise on the timescale of interest is

$$\sigma_{ins} = \sqrt{\sum_i \sigma_i^2}\,. \tag{1}$$

The photon noise on the timescale of interest is calculated via

$$\sigma_{phot} = \sqrt{\frac{1}{N_{phot}}}\,, \tag{2}$$

where N_{phot} is the number of photo-electrons registered by CHEOPS during the timescale of interest.

Using also the granulation noise σ_{stel}, the total noise (i.e., the uncertainty on the measured flux level) is calculated via

$$\sigma_{tot} = \sqrt{\sigma_{phot}^2 + \sigma_{stel}^2 + \sigma_{ins}^2} \tag{3}$$

for continuous observations, as well as for observations with a given efficiency (see below). $\sigma_{stel} = 0$ 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 South Atlantic Anomaly and periods during which the straylight exceeds observationally acceptable limits. The white noise components are adapted to account for this effect via

$$\sigma_{gap} = \sqrt{E/100}\;\sigma_{nogap}, \tag{4}$$

where σ_{nogap} is the precision in the absence of gaps, and σ_{gap} is the precision for a reduced observing efficiency, E (given in %).

3.2.1 Tabulated observing efficiency

Unless the "specify efficiency" option is activated, the observing efficiency is taken from a precomputed table. This table has been constructed from orbit calculations for 12 discrete 48-hour time windows spaced throughout one year, and contains of the optimal efficiency found for a grid of sky coordinates. This means that it is assumed that the target will be observed at the time of maximum efficiency.

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 stellar noise created by granulation ("flicker") is calculated for the timescale of interest. To do so, we use a grid of high time-resolution simulated light curves including only variations induced by stellar granulation. An example light curve is shown in Figure 2 . We binned these light curves in time intervals of up to 9 hours, and measured the RMS. These values were then fitted by a function of the form

$$A = c_0 + c_1 B + c_2^{c_3 B} \tag{5}$$

where A is the noise amplitude, B the bin size and c_i are coefficients fit for each light curve. An example is shown in the right panel of Figure 2. From this fit, and using the coefficients of the simulation with parameters closest to those of the target, the flicker noise amplitude is estimated at the timescale of interest.

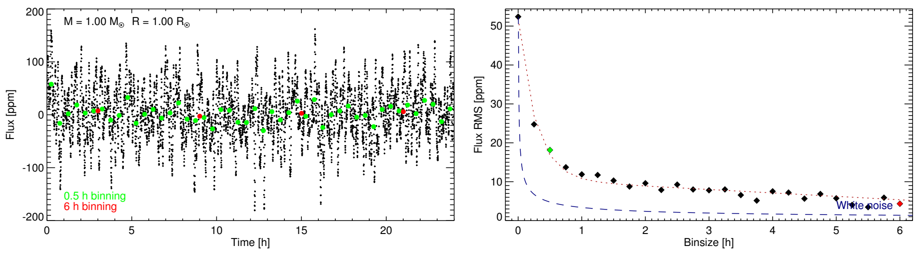

Figure 2: Left panel: a simulated flicker light curve, unbinned (black), and binned in 0.5 (green) and 6 h (red) intervals. Right panel: The RMS of the binned light curve against the bin size, together with a fit to approximate this relationship.

3.4 Stars

Input stellar parameters have been taken from Pecaut & Mamajek (2013), and are listed in Table 1.

For each star, the flux spectrum is calculated given the the magnitude and spectral type inputs. Using the effective temperature assigned for each spectral type, the number of photo-electrons per second measured by CHEOPS is calculated using a black body SED together with the CHEOPS global throughput (this includes the optical throughput and the quantum efficiency of the CCD). The flux spectrum of the star (n_{targ}) is normalized to the integrated flux of Vega in the V band, ($n_{V=0.035}$, Vega is assumed to be V = 0.035). Finally, the flux spectrum of each star is renormalized according to the value of input magnitude (mag_v) via

$$n_{targ} = 10^{\left(\frac{0.035-mag_V}{2.5}\right)} n_{V=0.035} \,. \quad (6)$$

Table 1: Stellar input parameters, reproduced from Pecaut & Mamajek (2013)

SP	M (Msun)	R (Rsun)	Teff (K)	L (Lsun)	BC	Mv	Mbol
F0V	1.59	1.79	7200	7.762	−0.01	2.51	2.5
F1V	1.5	1.64	7030	5.888	−0.01	2.79	2.78
F2V	1.44	1.61	6810	5.012	−0.02	2.99	2.97
F3V	1.43	1.60	6720	4.677	−0.03	3.08	3.05
F4V	1.39	1.53	6640	4.074	−0.04	3.23	3.19
F5V	1.33	1.46	6510	3.467	−0.04	3.4	3.36
F6V	1.25	1.36	6340	2.692	−0.05	3.7	3.65
F7V	1.21	1.30	6240	2.291	−0.06	3.87	3.81
F8V	1.18	1.25	6170	2.042	−0.07	4.01	3.96
F9V	1.14	1.23	6040	1.820	−0.08	4.15	4.07
G0V	1.08	1.12	5920	1.380	−0.09	4.45	4.4
G1V	1.07	1.12	5880	1.349	−0.1	4.5	4.4
G2V	1.02	1.01	5770	1.023	−0.11	4.79	4.68
G3V	1	1.01	5720	0.977	−0.12	4.86	4.74
G4V	0.99	0.99	5680	0.912	−0.13	4.94	4.8
G5V	0.98	0.98	5660	0.891	−0.13	4.98	4.84
G6V	0.97	0.94	5590	0.776	−0.15	5.13	4.98
G7V	0.96	0.95	5530	0.759	−0.16	5.18	5.02
G8V	0.94	0.91	5490	0.676	−0.17	5.32	5.15
G9V	0.9	0.88	5340	0.562	−0.21	5.55	5.34
K0V	0.87	0.82	5280	0.468	−0.22	5.76	5.54
K1V	0.85	0.81	5170	0.427	−0.26	5.91	5.65
K2V	0.82	0.76	5040	0.339	−0.29	6.19	5.88
K3V	0.78	0.73	4840	0.263	−0.41	6.57	6.16
K4V	0.73	0.69	4620	0.195	−0.55	7.04	6.48
K5V	0.72	0.71	4450	0.178	−0.67	7.25	6.58
K6V	0.7	0.65	4200	0.120	−0.86	7.88	7.07
K7V	0.64	0.61	4050	0.091	−0.97	8.3	7.33
K8V	0.63	0.61	3970	0.083	−1.08	8.58	7.5
K9V	0.61	0.54	3880	0.060	−1.22	9	7.78
M0V	0.6	0.53	3850	0.055	−1.3	9.16	7.9
M1V	0.53	0.47	3700	0.038	−1.53	9.8	8.27
M1.5V	0.5	0.46	3650	0.034	−1.57	9.97	8.4
M2V	0.48	0.43	3550	0.027	−1.65	10.3	8.65
M2.5V	0.44	0.39	3500	0.021	−1.76	10.7	8.94
M3V	0.39	0.37	3400	0.017	−1.97	11.14	9.17
M4V	0.22	0.26	3200	0.006	−2.59	12.8	10.2
M4.5V	0.18	0.24	3100	0.005	−3.05	13.57	10.5
M5V	0.15	0.20	3050	0.003	−3.28	14.3	11.0
M5.5V	0.12	0.15	3000	0.002	−3.8	15.51	11.7
M6V	0.1	0.13	2800	0.001	−4.36	16.62	12.2
M7V	0.09	0.12	2650	0.001	−5.06	17.81	12.7
M7.5V	0.08	0.11	2600	0.001	−5.46	18.42	12.9

M8V	0.077	0.11	2500	0.000	−5.79	18.88	13.0
M9V	0.065	0.10	2450	0.000	−5.73	19.26	13.5

References

Pecaut, M. J. & Mamajek, E. E. 2013, ApJS, 208, 9